H. A. Brown

A Course in Radio Engineering for Senior Electrical Engineering Students

A COURSE IN RADIO ENGINEERING
FOR
SENIOR ELECTRICAL ENGINEERING STUDENTS

BY

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I HEREBY RECOMMEND THAT THE THESIS PREPARED BY

Hugh Alexander Brown

ENTITLED A Course in Radio Engineering for Senior Electrical Engineering Students

BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE PROFESSIONAL DEGREE OF Electrical Engineer

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CONTENTS

INTRODUCTION

LECTURE AND RECITATION COURSE

List of Chapters.

CHAPTER I

FUNDAMENTALS OF OSCILLATORY CIRCUITS

I. The Lodge Experiment and its Application.

(a) Experiment described simply and carefully, concluding with explanation that the experiment contains the fundamental principles of so-called "resonant" circuits of Radio Telegraphy. The Lodge apparatus a radio transmitter and receiver.

II. Further Discussion of the Lodge Experiment.

(a) Essential differences between the circuits of power engineering and of above experiment pointed out and carefully explained. (Oscillatory character of current in primary and secondary circuits; resonance).

III. Oscillatory Character of Discharge of a Condenser Thru an Inductance and Resistance.

(a) The fundamental differential equation given, and brief discussion of use made of the equation.

(b) A simplified solution (assuming zero resistance) given, and discussed briefly. Use of the assumption $X_l = X_c$ to solve for frequency.

(c) The accurate solution discussed and solution given for the three particular cases, X^2 greater than, equal to, and less than $\frac{4L}{C}$.

(d) Discussion of the solution by V. Bush, and its significance.

IV. Damping of Oscillation-Decrement.

(a) Definition of "Decrement".

(b) Derivation of the expression $\delta = \frac{R}{2fL}$

(c) Derivation of the "energy expression" for decrement.

(d) Significance of the decrement in Radio Engineering.

V. Principle and Use of the Wavemeter.

(a) Description and explanation of action (use of detector and phones).

(b) Measurement of wave length and capacity.

VI. Measurement of Decrement, Simple Derivation of Bjerknes' Method.

$$\delta_1 + \delta_2 = \pm \pi \left(\frac{C_r - C}{C}\right) \sqrt{\frac{I^2}{I^2 - I_1^2}}$$

Brief description of method of measurement. The decrement.

CHAPTER II

ANTENNAS

I. The Simple Antenna.

(a) This simple form of Hertzian Oscillator explained.

(b) Physical concept of nature of the radiated wave.

(c) Various forms of Antennas mentioned and illustrated.

II. Constants of Antennas.

(a) Wave length, capacity, and inductance discussed, and relations given.

(b) Radiation Resistance explained, controlling factors.

III. Directive Properties of Antennas.

(a) General discussion including description of the Bellini-Tosi Aerial. Use of this type.

IV. The Loop Antenna.

(a) Three general classes of antennas.

(b) Principle of loop antenna explained.

(c) Constants - effect of area and number of turns.

(d) Directive properties.

V. Commercial Antennas.

(a) U. S. Navy Type.

(b) U. S. Army types.

(c) Ship Aerials.

(d) Marconi Directive type.

VI. Atmospheric Strays.

(a) Origin and nature of strays.

(b) Effect on various types of antennas.

CHAPTER III

THE DAMPED RADIO TRANSMITTER

I. Properties of Transmitters.

(a) Simple, inductively coupled, stationary gap transmitter described and explained.

(b) Impracticability of such a transmitter.

(c) Kind of damping desired decrements.

(d) Coupling Analogy described. Beats, free oscillations and double radiated wave lengths

II. Quenching.

(a) Reasons for quenching given.

(b) Methods of quenching described, representative types of gaps described.

III. Features of Transmitting Apparatus.

(a) High frequency resistance of closed and open circuits.

(b) Lumped and distributed capacity, and inductance effect on wave length.

(c) Power transformers discussed.

(d) Transmitting condensers discussed. Expression for necessary capacity derived.

IV. General Classes of Low Power Transmitters.

(a) Impulse or beat transmitters discussed, essential features. Nature of oscillations generated in this class, and method of producing oscillations.

(b) "Shock" or "impact" transmitters discussed, essential features. Nature of oscillations, method of producing.

(c) "Tone" circuits.

(d) Direct current excitation.

V. Description of a Representative Commercial Type of Each Class.

(a) Standard Marconi 2 K. W. ship set.

(b) Cutting and Washington set.

CHAPTER IV

UNDAMPED WAVE TRANSMITTERS

I. Distinction Between Damped and Undamped Waves.

II. High Frequency Alternators.

(a) Alexanderson Type described briefly.

(b) Principle of frequency transformer.

(c) Goldschmidt Alternator briefly mentioned.

III. Arc Generators.

(a) Principle explained.

(b) Nature of arc oscillations.

(c) Poulsen arc generators.

(d) Other types of arcs.

IV. Undamped Waves With Rotary Gap Dischargers.

(a) Marconi High Power System.

V. Other Methods of Producing Undamped Waves.

VI. Poulsen Federal System.

(a) U. S. Navy High Power Stations.

VII. Advantages and Disadvantages of Undamped Waves.

(a) Comparison made with damped wave transmitters.

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CHAPTER V

RADIO RECEIVING - VACUUM TUBES

I. The Simple Inductively Coupled Receiving Circuit

(a) Characteristic of crystal rectifiers.

(b) Explanation of action when using crystal detector.

(c) Modifications.

II. The Two Element Vacuum Tube.

(a) Space charge effect explained.

(b) Discussion of characteristics.

(c) Dependence of current on space charge, effect of positive body.

III. The Three Element Vacuum Tube (Audion).

(a) Description and notation

(b) Characteristic curves.

(c) Elementary theory for two and three element tubes. Variation of plate current with grid and plate voltage, and filament temperature.

IV. Operation of the Vacuum Tube as a Detector of Damped Oscillations.

(a) Description of action without grid condenser.

(b) Effect of grid condenser explained with aid of curves.

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V. Vacuum Tubes as Amplifiers.

(a) Characteristics and grid potential for true amplification.

(b) Applications in Power, Telephone and Radio Engineering.

VI. The Vacuum Tube Generator.

(a) Generating action explained.

(b) Beat reception explained.

VII. Beat and Amplifying Receivers.

(a) Practical types discussed.

(b) Amount of amplification.

VIII. Vacuum Tube Transmitters.

(a) High Power Tubes, features, and characteristics.

(b) Small power sets of the Signal Corps mentioned.

(c) Future developments, possibilities, and difficulties.

IX. Output Coefficients of Vacuum Tubes.

X. Commercial Forms of Radio Receivers.

CHAPTER VI

ELECTROMAGNETIC WAVES IN RADIO COMMUNICATION

I. Introductory.

(a) Material included in this chapter limited to its special application.

II. What Radiation Is.

III. Brief Descriptive Statement of Maxwell's Theory.

IV. Radiated Fields.

V. Derivation of the Radiated Magnetic Field.

(a) Expression derived for field radiated from an antenna.

(b) Derivation of received current.

VI. The Received Current in a Loop

(a) Derived equations given

VII. Range of Stations.

(a) Empirical formulae.

(b) Table of practical ranges.

VIII. Coils and Antennas as Radiators.

(a) Comparisons made.

CHAPTER VII

RADIO TELEPHONY

I. The Simple Radio Telephone.

(a) Description of necessary apparatus.

(b) Action explained.

(c) Carrier frequency.

II. Methods of Modulation.

(a) Definition of modulation.

(b) Methods outlined, and difficulties encountered.

III. Vacuum Tubes in Radio Telephony.

(a) Use as generators

(b) Use as modulators.

IV. Types of Radio Phone Transmitters.

(a) High power transmitters.

(b) Signal Corps Aeroplane Radio Phone.

(c) De Forest Radio Phone.

V. Receiving Apparatus for Radio Telephony.

VI. Duplex Radio Telephony.

CHAPTER VIII

RECENT DEVELOPMENTS IN RADIO ENGINEERING

I. High Speed Transmission and Reception.

II. High Power Stations.

(a) Marconi trans Pacific stations.

(b) U. S. Navy stations, special mention of - February, 1919 Annapolis station.

(c) The New Brunswick installation.

III. The Weagant Static Eliminator.

IV. Direction Finders.

V. Alexanderson Barrage Receiver, Unicontrol Receiver.

VI. Recent Experiments in Radio Telephony in 1915 and 1919.

LABORATORY COURSE IN RADIO TELEGRAPHY AND TELEPHONY

I. Laboratory Exercises

1. Resonance Curves of Oscillatory Circuits.

   (a) Instructions.

   (b) Description and Discussion of Apparatus.

2. Calibration of a Variable Condenser.

   (a) Instructions.

   (b) Apparatus

3. Measurement of Inductance and Capacity of an Antenna.

   (a) Instructions.

   (b) Apparatus.

   (c) Notes and discussion.

4. Current Voltage Characteristics of a Crystal Detector.

   (a) Instructions.

   (b) Notes and discussion.

5. Study of Radio Station Transmitter.

   (a) Instructions.

6. Adjusting and Tuning a Transmitting Station.

   (a) Instructions to student.

   (b) Discussion.

7. Characteristics of Three Element Vacuum Tubes.

   (a) Instructions to student.

   (b) Apparatus and arrangement.

8. Operation of Radio Receivers - Comparison of Crystals and Tubes.

    (a) Instructions to student.

9. Operation of a Vacuum Tube as a Generator.

    (a) Instructions to student.

    (b) Apparatus.

10. Measurement of Capacity - Resonance Curves.

    (a) Instructions to student.

    (b) Discussion of apparatus, and method.

11. Measurement of Decrement.

    (a) Instructions to student

    (b) Apparatus preferred, and needed.

12. Connection and Operation of a Radio Telephone in the Laboratory.

    (a) Instructions to student.

    (b) Apparatus.

    (c) Notes and discussion.

Ia. Suggested Additional Exercises.

II. Examination of Methods Described in Bulletin No. 74 Bureau of Standards.

1. Experimental Work on Apparatus and Methods.

SUMMARY

I. Lecture and Recitation Course.

II. Laboratory Course.

APPENDIX

I. Special Receiving Apparatus for Educational Institutions.

   1. Special Requirements.

   2. Apparatus Constructed at The Pennsylvania State College.

II. Special Equipment for Radio Laboratories

   1. Methods of Providing Voltage and Current at The Pennsylvania State College

   2. Vacuum Tubes.

STANDARD SYMBOLS AND ABBREVIATIONS USED

C - Capacity, farads.

L - Inductance, heuries.

R - Resistance, ohms.

R_z - Radiation resistance, ohms.

R_l - Leakage resistance, ohms.

E - Voltage, effective value.

I - Current, effective value.

E_o - Voltage, maximum value.

I_o - Current, maximum value.

i - Current, instantaneous value.

Q - Quantity, maximum, coulombs.

q - Quantity, instantaneous value, coulombs.

t - Time, seconds.

T - Period, seconds.

X_l - Inductive reactance, ohms.

X_c - Capacity reactance, ohms.

λ - Wave length, meters.

v - Velocity of light, 3×10^8 meters per second.

f - Frequency, cycles per second.

w - Angular velocity, radiaus per second, $2 \pi f$.

ϕ - Flux.

m.f. - Capacity, micro farads

m.h. - Inductance, millilheuries.

e.m.f. - Electro motive force.

REFERENCE ABBREVIATIONS USED

1.	Proc. I. R. E.	Proceedings of the Institute of Radio Engineers.
2.	Proc. A. I. E. E.	Proceedings of the American Institute of Electrical Engineers.
3.	Fleming	"Principles of Electric Wave Telegraphy and Telephony" by J. A. Fleming.
4.	Zenneck	"Wireless Telegraphy" by J. Zenneck.
5.	Lauer and Brown	"Radio Engineerineering Principles" by Lauer and Brown.
6.	Mills	"Radio Communication" by John Mills.
7.	Jansky	"Principles of Radio Telegraphy" by C. M. Jansky.
8.	Pierce	"Principles of Wireless Telegraphy" by G. W. Pierce.
9.	Bul. No. 74	"Radio Instruments and Measurements" Circular No. 74 of Bureau of Standards.
10.	Fleming, Elementary Manual	An Elementary Manual of Radio Telegraphy and Telegraphy for Students and Operators, by J. A. Fleming.

INTRODUCTION

I. Reasons For Collecting Material For This Thesis.

Radio Engineering for Electrical Engineering students is usually an elective course, and as such, is, or should be, classed with the other commonly given elective subjects; namely, Electric Railways, Illumination, Telephony, etc. More or less attention is paid these subjects in various Engineering schools, and the question as to whether they should be offered is a debatable one. Without going far into both sides of this subject it may be safely said that if their adoption makes inroads upon the time that the student should devote to a thorough grounding in the fundamentals of Direct and Alternating Currents these elective or application courses do as much harm as good.

A course in Telephony will not make a Telephone Engineer out of the student, so it is concluded by many that the four or six semester credits allotted to these subjects should be devoted to fundamentals, and if not for these latter they should be allotted to additional courses in Economics, etc.

While recognizing that one of the above mentioned elective courses will not make a specialized engineer of the student, the writer of this thesis believes that they may be of great value in helping the student to decide what branch of Electrical Engineering would appeal to him the most. This is a very perplexing question to the student, more so, sometimes, than the teachers realize. A student may be undecided as to which of two branches of the profession would appeal to him more, and if he will include two of these subjects in his electives he will in most cases see which better suits his temperament and peculiar ability or talent. If the elective subject is to accomplish this purpose it should do two things; first, it should give the student a fairly good grasp of the elementary but fundamental principles, and second, it should give him a concrete idea of present day engineering practice in that branch of the art.

The most serious limitation of existing text books on the subject of Radio Engineering is that they do not fulfill the two requirements just mentioned. Some books dwell too fully upon the mathematical principles, and illustrate engineering practice which is entirely obsolete. There are also authors who start out with simple explanations of alternating current phenomena assuming that the student is not familiar with them, and then assume in the latter chapters of the text that the reader is a well grounded senior student of Electrical Engineering. Other authors treat the principles mathematically using an

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arbitrary expression for the derivative so that it may be understood by the nonmathematical student, and one who examines such a book will decide that the subject is so treated that no nonmathematical student could understand it. Ambiguous physical explanations and lack of derivations or reasons for certain fundamental relations are among the many additional criticisms the writer frequently makes of existing texts, including the latest books published on this subject.

The treatment of the subject is made in as brief and concise language as possible, and the subject matter itself is limited to the descriptions, derivations, and discussions which will give the student a good foundation so that he can follow up any book or paper on the subject without experiencing any difficulty with the principles involved. A common fault of text books on this subject is that too much space is given to discussions of various circuits and apparatus which are esentially alike in principle. One particular instance which came to the writer's notice was that of a text in which full descriptions of the operation principles of about a dozen forms of vacuum tube oscillators were given, taking up each form separately. Too much treatment of details certainly has a tendency to obscure the fundamental principles. The method followed by the writer was to treat fully one commonly used form of apparatus or circuit, explaining its working principles, and then to refer only briefly to other commonly used forms.

There are practically no useful instructions in any text book on the performing of an experiment or exercise in the radio laboratory. Text books do not describe experiments as does a laboratory manual, hence are of little value in the laboratory. For instance, various vacuum tube oscillators for the laboratory which are not practical are described, and instructions are not given as to what to do in case the oscillator suddenly ceases to function, or the plate glows at a red heat, etc. The writer has found out that the performing of laboratory exercises from information gleaned from texts is a discouraging experience. Texts do not state that many experiments are not easy to perform, that adjustment in many cases is unreliable and difficult.

In the preparation of the material the writer has taken pains to meet the two requirements mentioned previously, to give a thorough understanding of the most fundamental elements, and to present a concrete survey of present day engineering practice.

II. Material for the Lectures Comprising the Course

The aim of the writer is to provide a course that can be given either in one or two semesters depending upon the time allowed in the curriculum. If only one semester is to be devoted thereto the material should be covered using a schedule of one recitation per week if the students are provided with copies of

the eight chapters and diagrams. If the material is given in lectures some allowance must be made for occasional recitations and quizzes. If two semesters are allowed for the course a little more time is taken to the course so that the eight chapters are completed as soon as it seems advisable during the second semester, and not later than the middle of this semester. The remainder of the semester is devoted to seminary work in which each student is assigned certain material in one of the references cited in the eight chapters or in some recent publication. The student may select some phase of the subject in which he is especially interested, and after preparing himself is asked to give a talk or lecture before the class upon what he has read. The student's interest is greatly increased in this way. Since the course at the institution in which the writer is at present employed covers two semesters this latter plan is followed. In the preparation of the material the writer has taken pains to meet the two requirements mentioned previously, namely, to give a clear understanding of the most fundamental principles and to present a concrete survey of present day engineering practice. He assumes that the student is familiar with the mathematics required of the Electrical Engineer, and assumes that the student does not understand the peculiar physical phenomena of radio circuits. To the student of electric power apparatus and circuits the radio circuit is often puzzling, hence clear physical explanations are striven for in this course.

Fundamental mathematical relations are derived omitting any involved mathematical operations but physical reasoning is given first. A serious fault of many writers of text books on Electrical Engineering is the impression they give that certain things happen because of the form of a certain equation or formula. For instance, an author will state that the speed of a shunt motor increases when the field current is decreased because ϕ is in the denominator of the formula for speed, and hence speed increases because ϕ, which depends upon the field current, decreases. This author should explain in a physical way the inherent changes in the machine itself that cause the increase of speed.

The material in the chapters is taken partly from eight of the best known texts, and partly from papers in the Proceedings of the Institute of Radio Engineers, and of the American Institute of Electrical Engineers. A list of these books is given in the table of reference abbreviations at the beginning of this thesis. Many of the explanations are given from a different starting point, or view point from those in any of these texts in an attempt to make the phenomena more clearly understood. In many cases ideas given by the various authors were combined. The student is frequently referred to certain pages in these texts, proceedings, and other periodicals. Only the most essential principles can be covered in this course, but if the student is deeply interested in the subject, and wishes to specialize in it, these references should be of considerable help to him. A

few derivations and several explanations were not to be found in any of these texts. It seemed to the writer that some of these were very fundamental, and could not be omitted in this course. For instance, every text that has come out in recent years has failed to give the derivation of the expression for logarithmic decrement; neither is a clear physical explanation given as to why a coupled circuit radiates two wave lengths.

It seemed to the writer that the student's interest would be stimulated if by some means the description and explanation of a simple experiment illustrating the principle of a radio signalling system could be taken up at the very first. The phenomena attending the experiment should then be taken up and discussed at some length. Accordingly the first chapter begins with a description of Lodge's experiment in order that the student may at once understand why it is necessary to discuss condenser discharge phenomena, etc. before taking up the radio transmitter.

The material was arranged so as to have as few chapters as possible consistent with the ground covered. Resonance of coupled circuits is therefore discussed under "Properties of Transmitters" in Chapter III. For the above reason also the discussions of receiver circuits and of vacuum tubes were combined into one chapter. The writer came into touch with a method of explanation used in some instructional work in the U. S. Army in which a thing was repeatedly referred to by restating its principle function or purpose so as to thoroughly fix it in the mind of the student. This idea is carried out in several places in this thesis, and, although it may be criticized from the point of view of good English composition, the writer believes it will aid in fixing fundamental concepts in the student's mind.

III. Laboratory Course.

In laying out the laboratory course in was assumed that the interest of the student would not be aroused by simply a course in radio laboratory measurements, but that it was also necessary that he be allowed to connect, adjust and operate actual radio transmitting and receiving apparatus. Hence the writer's original plan of sixteen laboratory exercises was abandoned in favor of the twelve, including the important commercial radio measurements of capacity, inductance, wave length and logarithmic decrement. The experience of the writer during the present semester led to this conclusion.

Instructions are given for each exercise with a diagram of connections in most cases. For each exercise a discussion is given of any particular apparatus or adjustment. The term "exercise" is used instead of "experiment".

As previously stated good results are difficult to obtain in many of the laboratory measurements especially those in which buzzer excited circuits and crystal detectors are used. Some discussion (supplementing the exercises) is devoted to the needed apparatus and methods for best results from students. The discussion is demonstrated by the results of a few tests made to show both apparatus and method efficiency. As the course is arranged at present one three hour laboratory period is allowed each week for the laboratory work with only one semester credit. One credit hour is also allowed for the lecture or recitation work which comprises a one hour period each week. This makes a total of two credit hours for the course. One laboratory period is devoted to performing the exercise and the following period to the preparation of the report and to the procuring of additional data if necessary. A new exercise is then performed every other week. This plan is followed in all similar elective courses requiring laboratory work at the institution where the writer is employed at present, and, as this plan seemed to be an excellent one the writer arranged the laboratory course accordingly. The twelve prescribed exercises are completed by the middle of the second semester and the remainder is devoted to some additional exercises or some original experimental work. During the latter part of the present second semester the students will experiment with various forms of vacuum tube radiophones in order to determine which is the most satisfactory for a permanent installation at the institution. If the course is limited to one semester the laboratory exercises prescribed can only be completed by performing one exercise each week, and then it will probably be necessary for the instructor to set up the apparatus if any results are to be obtained. This will no doubt detract from the interest of the student in the course and from the value of the latter.

A COURSE IN RADIO ENGINEERING

for

SENIOR ELECTRICAL ENGINEERING STUDENTS

Lecture and Recitation Course

CHAPTER I

FUNDAMENTALS OF OSCILLATORY CIRCUITS

1. The Lodge Experiment and its Application

Sir Oliver Lodge performed a classical experiment which beautifully illustrates a radio telegraph system, so a description of this experiment is of much value to the student. Referring to Fig.1 the condenser C_1 is charged by means of the induction coil I. When the voltage of the condenser has reached a sufficiently high value a spark discharge occurs across the gap S_1. It should be noted that the electrodes of the spark gap are connected to both condenser plates (or coatings of the Leyden jar) through the rectangular conductor R. A second condenser or Leyden jar is placed near the first (say ten inches away) and the plates or coatings are connected to long rods, A and B, as shown. A third rod D is arranged to slide along rods A and B making contact with them. A spark gap S_2 of about one millimeter is connected across the condenser C_2 as shown. When the induction coil is started C_1 discharges each time the interrupter breaks contact or at the instant of maximum voltage of I, so that spark discharges occur at S_1 with a group frequency which is equal to that of the interrupter. The apparatus is placed so that the planes of the rectangular conductors are parallel and adjacent to each other as shown in the Fig. and the rod D is moved along A and B to a position where a small discharge occurs across gap S_2. At the best position of D this discharge is most intense, and as the rod is moved in either direction from this point the discharge of S_2 grows weaker and weaker and finally dies out. If the two condensers and their discharge circuits be placed still farther apart it will be found that the adjustment of A cannot be varied through as wide a range, and for a certain separation of the two parts of the apparatus it will be found that D must be adjusted carefully to get a discharge at S_2. At this position a very little movement causes this discharge to cease.

Lodge performed this experiment to illustrate the phenomenon of "resonance" of so called condenser circuits. In this experiment several principles are met with in the study of radio telegraph circuits such as transmitter, receiver, tuning, resonance, coupling, etc. The discharging condenser excited by the induction coil and the path of its discharge current is similar to a transmitter and will be known as the "primary".

The condenser C_2 and its discharge path correspond to the receiving circuit and will be termed the "secondary". Adjusting the rod for maximum discharge at S_2 corresponds to "tuning" a receiver, and the variation of the relative positions of the primary and secondary varies the "coupling". These will be studied later, and an understanding of them requires first a study of the phenomena of the action within each condenser circuit.

First consider the primary condenser discharge circuit which consists only of condenser C_1 conductor R and spark gap S_1. Note that the secondary of the induction coil is not included, it merely serves to charge the condenser to a high potential. When the voltage of the condenser reaches a value exceeding the sparking voltage of the gap the latter breaks down and the charge Q rushes along the conductor R in the form of a discharge current. The potential energy of the charge stored in the condenser, $1/2\ C\ E^2$, is now converted into the kinetic energy of the moving charge, $1/2\ L\ I^2$. The current is of the sine wave form; $I = \frac{dq}{dt}$, and $q = Q \sin wt$. The inertia of the magnetic field causes the charge to continue to move until it is again stored in the condenser but oppositely from the first assumed charge. This also builds up the voltage across the condenser and also across the gap in the opposite direction until the gap breaks down and the charge moves around the rod conductor in the reverse direction until the condenser is again charged with the same plate positive as in the first case. The same cycle is repeated, but with less intensity, and the process of charging and discharging goes on with decaying intensity until the energy of the charge is finally dissipated in the resistance of the path of current. The term "discharge of the condenser" is usually taken to mean the flow of the original charge back and forth from one plate of the condenser to the other until it has died out. This all occurs in a very short period of time, say .0005 second and after this the interrupter breaks and the high induced voltage places a new charge in the condenser, and the process is repeated. A simple but striking analogy to the discharging action of the condenser is the pendulum. Suppose a ball suspended by a string is pushed to one side. It acquires potential energy due to being raised slightly. When it is released it returns to its original position of rest with increasing velocity, and when it reaches this position it has acquired considerable velocity. Owing to its acquired kinetic energy it will continue to swing until it reaches a position nearly as far to the opposite side of its original position of rest as it was to one side at the start of the swing. All familiar with the motion of a pendulum know that it will continue to swing to and fro from side to side with gradually decreasing amplitude until the energy given to it in the original push has been dissipated in the form of heat due to air friction on the ball and friction in the string. The charged condition of the condenser corresponds to the

extreme position of the pendulum ball at the start of the swing when the energy is stored in potential form. When the discharge current reaches a maximum it corresponds to the mid-position of the pendulum in its swing, and the energy has nearly all been transformed into kinetic form (except for a small amount that has already been dissipated). If a graph be plotted between amplitude of vibration of the pendulum and time as abscissa a simple harmonic curve, or a familiar sine wave will be obtained. The same will result if discharge current be plotted against time. It must be remembered that the sine wave of current will gradually decrease in amplitude (maximum value) due to the dissipation of energy. This is known variously as decay, attenuation, or "damping" of the current. The form of discharge curve is shown in Fig. 2. The term discharge current will represent the alternate charging and discharging of the condenser until the energy dies away as was previously mentioned.

II. Further Discussion of the Lodge Experiment.

The rate at which the condenser will charge and discharge will depend upon certain factors and to explain this another analogy will be appropriate here. Suppose a thin strip of wood to be clamped at one end in a vise, and if the free end have a weight fastened to it it will vibrate at a certain rate. If the weight on the free end be increased the rate of vibration will be made slower, the time for one complete vibration will be greater. Again, if the strip of wood be exchanged for another which is stiffer the rate of vibration will be increased, or the time for one vibration will be lessened. The rate of charging and discharging of the condenser is dependent upon the electrical elasticity, or capacity of the circuit, and upon the electrical weight or inductance of the circuit. Later on this will be shown mathematically but it is necessary here to have a clear physical understanding of the phenomena and the factors governing them. Increasing the capacity or inductance produces the same effect upon the rate of discharge or rate of oscillation of the original charge as increasing the weight of the ball or the flexibility of the strip does in the case of the vibrating strip in the vise; i.e., it increases the time required for one complete vibration or oscillation, or lowers the rate or frequency. The time for one complete oscillation of the condenser charge is indicated on Fig. 2, and is the time required for the condenser to discharge, A to B, charge in the opposite direction, B to C, discharge again, C to D, and finally charge in the original direction up to full charge, D to E. The time required for one complete oscillation is represented by t. The wave of e.m.f. will be discussed presently. Recalling the manipulation of Lodge's experiment the sliding rod of the secondary condenser circuit ($ABDC_2S_2$) was moved until the spark discharge at gap S_2, Fig. 1, was at its brightest. Moving the rod changed the length of the path of the secondary circuit, changing the inductance of this circuit and therefore the period of oscillation of this circuit. When the period of the

secondary circuit was the same as that of the primary circuit the influence of the latter upon the former was greatest, and the "waves" sent out by the primary generated potentials in the secondary which were of the same period as the natural period of the secondary itself, and therefore the maximum oscillatory current was set up in the secondary. A simple analogy illustrating this is two ball and string pendulums tied to the same flexible support such as a stretched horizontal wire. If one pendulum is set in vibration it will set the other in vibration only when the length of the second is nearly that of the first. The two circuits like the two pendulums are "tuned" and are said to be in resonance.

From the student's knowledge of resonance of series circuits he knows that the voltage drop across the condenser is great at resonance, and may be greater than the impressed voltage, and in this case it is large enough to cause a spark across the small gap S_2. It is evident to him that this e.m.f. could not be generated by simple induction such as in a transformer since the induction of the primary on the secondary must be very weak. In fact the potentials generated in the secondary are very small hence the large voltage at S_2 must be due to resonance in a series circuit. To understand more fully what goes on in the primary and secondary circuits of this experiment, and in the space between them requires a more careful study of each part separately.

III. Oscillatory Character of Condenser Discharge.

Referring to Fig.2 the dotted curve represents the e.m.f. of the condenser. It is maximum at the zero of time abscissa, and reduces to zero as the discharge current reaches its maximum. The e.m.f. wave shows the condition of the condenser at any time, that is, points of maximum positive and negative charge, zero charge, and charge at any instant for $e = \frac{q}{c}$. The student should note that the current lags 90° behind the e.m.f. and it should be remembered that the e.m.f. is that of the condenser. There is no impressed e.m.f. during discharge. In ordinary series or parallel circuits where a condenser is used the current in the condenser leads the e.m.f. impressed upon it by 90°, but in this case the e.m.f. shown is that due to the charge in the condenser and is equal and opposite to the impressed e.m.f. It should also be noted that a condenser circuit with the condenser discharging as in the Lodge experiment is different with respect to frequency of the current from the power circuit containing a condenser. In power circuits the frequency is that due to the alternations of the impressed e.m.f., while in the case of a condenser discharge the frequency is determined by the inductance and capacity of the condenser circuit since the period is dependent upon these constants. The secondary voltage of the induction

coil which gave the condenser its original charge is considered as entirely removed. The relation between frequency and period is familiar, the number of cycles or oscillations per second being the reciprocal of the period or time for one oscillation in seconds.

When a voltage is impressed upon a circuit containing R, X, and C the familiar expression

$$E = i\,r + L\frac{di}{dt} + \frac{1}{c}\int i\,dt$$

holds. For a charged condenser with its plates connected by R and L the voltage drops across the R L and C must add up to zero since it is a closed series circuit. Hence

$$i\,r + L\frac{di}{dt} + \frac{1}{c}\int i\,dt = 0$$

$i\,r$ is the voltage drop through the resistance, $L\frac{di}{dt}$ that through the inductance, and that through the condenser is $\frac{q}{c}$ where $q = \int i\,dt$. The solution of this equation gives some very important useful relations and formulae for radio circuits. It gives, first of all, an expression for obtaining the period or frequency of the oscillatory discharge, it shows under what conditions the discharge is not oscillatory, and gives an expression for the rate at which the energy of the discharge is dissipated in the resistance. These relations are very important in radio engineering. The general solution of this equation is not possible, but particular solutions assuming certain values for the constants can be obtained; these solutions are the most useful. Before taking up the solution of expressions for current an approximation will be considered which gives an expression for the frequency of the oscillation. The resistance of such circuits as the secondary in the Lodge experiment is so low that it may be neglected. Then

$$L\frac{di}{dt} + \frac{1}{C}\int i\,dt = 0$$

$$\text{or} \quad L\frac{di}{dt} + \frac{q}{C} = 0$$

$$\frac{di}{dt} + \frac{q}{LC} = 0 \qquad (a)$$

Now $i = \frac{dq}{dt}$, hence $\frac{di}{dt} = \frac{d}{dt}\left(\frac{dq}{dt}\right) = \frac{d^2q}{dt^2}$

Substituting in (a), $\frac{d^2q}{dt^2} + \frac{q}{LC} = 0$

Again $q = Q \sin. wt$

$$\frac{dq}{dt} = wQ\cos. wt$$

$$\frac{d^2q}{dt^2} = -w^2 Q \sin wt$$

$$= -w^2 q, \text{ since } q = Q \sin wt$$

Substituting in (a), $-w^2 q + \dfrac{q}{LC} = 0$

$$w^2 q = \frac{q}{LC}$$

or $$w^2 = \frac{1}{LC}$$

whence $$w = \frac{1}{\sqrt{LC}} = 2\pi f$$

Since q was assumed to be equal to Q sin $(2\pi f t)$ where f is the frequency.

finally $$f = \frac{1}{2\pi\sqrt{LC}}$$

or $T = 2\pi\sqrt{LC}$ seconds

The equation for the period agrees with the preliminary physical explanation in that the greater the capacity or inductance the slower the rate of oscillation. The above expressions for f and T hold very closely and are as fundamental in radio engineering as Ohms law is in direct currents. The above expressions can be quickly derived in another way. The circuit oscillates at its natural frequency, and therefore the frequency of resonance for the case of a resonant series circuit. Since the current in the secondary is due to resonance, and

since $$I = \frac{E}{\sqrt{R^2 + (X_L - X_C)^2}}$$

For resonance I is maximum and $X_L = X_C$

$$2\pi f L = \frac{1}{2\pi f C}$$

or $$f = \frac{1}{2\pi\sqrt{L\,C}}$$

$$\text{or} \quad f = \frac{1}{2\pi\sqrt{LC}}$$

The above simplified solutions do not give an expression for current, and from the form of the differential equation

$$i\,r + \frac{L\,di}{dt} + \frac{1}{c}\int i\,d\,t = 0$$

it is evident that the current i is the unknown to be solved for. The mathematical work in the solution of this equation is laborious and will not be undertaken here, but the various particular solutions will be given and simplified. Expressions for current are obtained as follows:

Case 1 – when $R^2 < \frac{4L}{C}$

$$i = \frac{2E_o}{\sqrt{\frac{4L}{C} - R^2}}\,\varepsilon^{-\frac{Rt}{2L}}\left[\sin\left(\frac{\sqrt{4LC - R^2C^2}}{2LC}\right)t\right] \quad (1)$$

as first worked out by Kelvin. E_0 is the maximum voltage of the condenser at start of discharge. The maximum charging current is, from Ohms law for a.c. circuits,

$$I_o = wCE_o \quad \text{where} \quad w = 2\pi f$$

Then $$i = \frac{I_o}{wC\sqrt{\frac{4L}{C} - R^2}}\,\varepsilon^{-\frac{Rt}{2L}}\left[\sin\left(\frac{\sqrt{4LC - R^2C^2}}{2LC}\right)t\right]$$

Neglecting the R^2 terms in the above equation as R is small,

$$i = \frac{I_o}{w\sqrt{LC}}\,\varepsilon^{-\frac{Rt}{2L}}\left[\sin\left(\frac{1}{\sqrt{LC}}\right)t\right]$$

But it was shown in the preceding derivation that

$$w = \frac{1}{\sqrt{LC}} = 2\pi f$$

Hence $$i = I_o\,\varepsilon^{-\frac{Rt}{2L}}\sin wt. \qquad (2)$$

Comparing equations (1) and (2) it can be seen that the more exact expression for w is

$$w = \sqrt{\frac{4LC - R^2}{2LC}} = \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$$

and when R^2 is neglected, $w = \sqrt{\frac{1}{LC}}$

$$\text{or } f = 2\pi\sqrt{LC}$$

In equation (2) $E - \frac{R\,t}{2\,L}$ is known as the "damping factor" and evidently it reduces the value of i as the time t increases. Sine w t is the sine function factor the discharge is a decaying sine function. The currents in both primary and secondary of the Lodge experiment, and in the radio transmitter are of this nature, with some modifications which will be explained later.

Case II. — when $R^2 = \frac{4L}{C}$

$$i = \frac{E_o t}{L}\,\varepsilon^{-\frac{Rt}{2L}} \qquad (3)$$

Inspection of equation (3) shows that the discharge current is a unidirectional impulse rising and then dying away as t increases. This is to be expected when an analogy is considered. The friction on the pendulum ball may be imagined to increase, and at a certain value all vibration would be damped out on the first swing from extreme position to zero. This value of resistance, $R^2 = \frac{4\,L}{c}$ is called the critical resistance, and at this value the discharge just becomes non-oscillatory.

A photograph of such a discharge is shown in Proc. I.R.E., Dec. 1918, P. 297 Fig 2.

Case III. — when $R^2 > \frac{4L}{C}$

$$i = \frac{E_o}{\sqrt{R^2 - \frac{4L}{C}}}\left\{\varepsilon^{-\frac{t}{T_2}} - \varepsilon^{-\frac{t}{T_1}}\right\} \qquad (4)$$

where $$T_1 = \frac{2LC}{RC - \sqrt{R^2C^2 - 4LC}}$$

and $$T_2 = \frac{2LC}{RC + \sqrt{R^2C^2 - 4LC}}$$

Equation (4) is the general expression for current for all values of R^2 above $\frac{4L}{C}$ and is non oscillatory as in Case II. However, in the case of equation (4) the current amplitudes for small values of t are greater than for equation (2); and this is to be expected since the greater the ratio of resistance to inductance the quicker the current builds up to its maximum value. As the resistance becomes great the maximum amplitude of current becomes smaller. Mention is made here of this type of discharge because it finds an application in a very efficient type of transmitter described in Chapter III, viz. the shock or impact type of transmitter.

The expression $f = 2\pi\sqrt{LC}$ makes it an easy matter to closely predetermine the frequency of the oscillatory circuit L and C. For reasons explained in Chapter II f varies from 30,000 cycles to 3,000,000 cycles. Suppose a condenser of a capacity of .001 micro farad is connected to an inductance of .04 millihenries, or about eight turns of wire on a ten inch helix.

$$f = \frac{1}{2\pi\sqrt{\frac{.001}{10^6} \times \frac{.004}{10^3}}} = \frac{10^7}{2\pi\sqrt{4}}$$

$$= 796{,}000 \text{ cycles.}$$

Dr. V. Bush has given a solution of the fundamental differential equation which assumes a leakage resistance and he has shown that by making this resistance a certain value the frequency can be made exactly equal to $\frac{1}{2\pi\sqrt{LC}}$

IV. Damping of the Oscillation-Decrement

It has been mentioned that the rate at which the energy is dissipated depends upon the resistance. In Fig.2 the resistance is low and the discharge current or oscillation decays slowly, while in Fig. 3 the resistance is high and the current dies out quickly. The oscillation in Fig. 3 is said to be more highly damped than in Fig. 2 . The rate of decay is called the "damping" of the oscillation. The ratio of any two successive maximum positive amplitude may be taken as a measure of the damping and is called the "decrement" of the oscillation. Then the decrement of the oscillation in Fig.3 is greater than in Fig. 2. Considering again the general expression for oscillatory discharge, equation (2)

$$i_o = I_o \varepsilon^{-\frac{Rt}{2L}} \sin wt$$

At A, Fig. 3, the abscissa of maximum current w t = 90° on the current wave
and

$$i_1 = I_0 \varepsilon^{-\frac{Rt}{2L}} \qquad (i_1 = AA' = I_0)$$

At B, the next successive abscissa of maximum current w t = 450°

$$i_2 = I_0 \varepsilon^{-\frac{Rt}{2L}} \qquad (i_2 = BB')$$

where T is 360°, the period of the oscillation.

Now $T = \frac{1}{f}$

where f = **number** of oscillations per second or frequency.
The decrement was defined as

$$\frac{i_1}{i_2} = \frac{\text{ordinate } AA'}{\text{ordinate } BB'}$$

$$= \frac{I_0 \varepsilon^{-\frac{Rt}{2L}}}{I_0 \varepsilon^{-\frac{R(t+\frac{1}{f})}{2L}}} = \frac{1}{\varepsilon^{-\frac{R}{2fL}}}$$

or Decrement = $\varepsilon^{\frac{R}{2fL}}$

It is more practical to use the logarithm of this expression so as to get rid of the exponent, and use the term "logarithmic decrement"- symbol δ

then $\delta = Log_\varepsilon \varepsilon^{\frac{R}{2fL}} = \frac{R}{2fL}$

By substituting the relation $2\pi f = \frac{1}{\sqrt{LC}}$ in equation (5) other expressions may be derived for δ, such as

$$\delta = \pi R \sqrt{\frac{C}{L}} = \frac{\pi R}{wL}$$

The decrement and hence the logarithmic decrement depends upon the rate of dissipation of the energy of the oscillation. If I^2R represents the power consumed, $\frac{I^2R}{f}$ is the energy dissipated per cycle, since the watts (I^2R) equals joules per second, and f represents cycles per second. Hence $\frac{I^2R}{f}$ is the energy dissipated per second in joules. The average energy stored at maximum current is $\frac{LI^2}{2}$, and the average energy stored at the maximum of current is $\frac{1}{2}$ L I_0^2. Since $I_0^2 = 2I^2$ the average energy stored at maximum current is LI^2. If the logarithmic decrement is defined as one half the ratio of the energy dissipated per cycle to the average energy stored at maximum current.

$$\text{or} \quad \delta = \frac{1}{2}\left(\frac{\frac{I^2R}{f}}{LI^2}\right) = \frac{R}{2fL}$$

The reason one half the ratio is taken is to give the same expression as in the previous derivation. These expressions for logarithmic decrement assume a low value of R, and it is obvious that δ will have a small value. An oscillation in which δ is 0.3 is very highly damped, the value of δ in Fig. is about .2.

It is very important to know what the value of the logarithmic decrement is in the design of a radio transmitter. The efficiency of the transmitter and the character of the radiated waves depend upon the value of δ, for the radiated wave δ should be less than .2. This quantity must be calculated and later measured for every commercial form of transmitter and antenna built, from $\frac{1}{4}$ K.W. up to the largest now in use, about 1000 K.W. The method of measuring this quantity will be considered presently.

V. Principle and Use of the Wavemeter

Before going into the method of measuring wave length and logarithmic decrement it will be well to discuss in an elementary manner the meaning of wave length and its relation to other factors. It will be remembered that the secondary circuit in the Lodge experiment was influenced by waves radiated from the primary circuit at a frequency of radiation equal to the oscillation frequency of the primary. During one cycle or complete oscillation of the primary a radiated wave will have time to travel a certain distance, depending upon the period of the primary and the velocity at which the wave travels. The velocity of the wave equals the frequency with which the waves are set up multiplied by the distance which one wave travels before the next succeeding wave is started, this time interval being the period of the exciting circuit or primary. For instance, if a series of traveling impulses are generated at the rate of 100 per second and each impulse travels 200 meters before the following impulse is started, the velocity of the impulses is 20,000 meters per second. Obviously the distance between the successive impulses as they are traveling in space remains constant at 200 meters, the wave length. The general relation, then, is

$$v = \lambda f \qquad or \qquad \lambda = \frac{v}{f}$$

The velocity of all waves in radio phenomena is very nearly 3×10^8 meters per second, the velocity of light. A better understanding of the nature of waves will be acquired when Chapter VI is studied.

The wavemeter is simply an oscillating circuit consisting of an inductance and capacity connected together with a hot wire galvanometer in series to indicate the amount of current induced in the circuit, and the setting of the variable condenser

for resonance. The wavemeter functions exactly like the secondary circuit of Lodge's experiment, except that the capacity of the variable condenser is varied until resonance is obtained. This condition is shown by maximum deflection of the hot wire ammeter, or galvanometer and thermocouple, should it be used. A crystal detector and telephone receiver may be connected to the wavemeter in various ways to the wavemeter and resonance is indicated by maximum sound. The explanation of the action of a crystal detector is found in Chapter V. Fig.4 shows several wavemeter circuits with the various types of resonance indicating devices. Resonance is obtained when the natural frequency, $\frac{1}{2\pi\sqrt{LC}}$ of the wavemeter circuit is the same as that of the primary exciting circuit P. If the capacity and inductance of the wavemeter are known for the condition of resonance the frequency can be calculated from f = $\frac{1}{2\pi\sqrt{LC}}$ and the wave length of the incoming wave is

$$\lambda = \frac{V}{f} = 2\pi V\sqrt{LC} = 6\pi \cdot 10^8\sqrt{LC}$$

L is taken in henries, and C in farads. For commercial types of wavemeters a scale on the rotary plate shaft of the variable condenser is calibrated directly in wave lengths, or a calibration curve is prepared showing the wave length for any position of the variable condenser. It should be evident to the student how the wavemeter may be used to measure the capacity, inductance, or frequency of an oscillatory circuit. An interesting and instructive experiment with a wavemeter is the determination of resonance curves. If a wavemeter be excited by coupling to an oscillatory circuit P, Fig. 4, the current in the wavemeter will vary with the capacity of the wavemeter condenser as shown by curve A of Fig. 4 . The point A is the point of resonance, and it will be noted that the point is very sharply defined, and the current has increased enormously. At this point $I = \frac{E}{R}$, and wavemeters are made so that R is small. Now if resistance be put in the exciting circuit curve B will be obtained, and it will be noticed that the resonance point is less sharply defined and the resonant current is lower. For increased resistance curve C is obtained. The lower the resistance the sharper the resonance, hence the sharpness of resonance is taken as the reciprocal of resistance, and since $\delta = \frac{R}{2fL}$, sharpness of resonance varies as $\frac{1}{\delta}$. It is assumed here that the circuit P and the wavemeter are far apart, and the one has no effect on the other. The experiment may be repeated with a variable resistance in the primary and similar resonance curves will be obtained, the sharpest resonance being obtained for lowest primary resistance, and hence lowest decrement of emitted wave. Resonance of oscillatory circuits closely coupled, that is,

placed very near each other, will be discussed in Chapter III.

VI. Measurement of Decrement

The wavemeter may be used to measure the decrement, or the logarithmic decrement of an oscillatory circuit. Using the expressions derived previously would require measurement of the resistance and at frequencies of 50,000 to 3,000,000 cycles skin effect increases the value of R many times its ohmic value. The logarithmic decrement may be obtained by observing the value of the current in a wavemeter circuit at resonance, and then inserting a known high frequency resistance and observing the new value of current. Then the resistance is easily obtained by the use of Ohm's law. For several reasons this method is not in practical use for decrement measurements, chief among these is the reason that it is not easy to determine the value of the inserted resistance, and the results would vary greatly with the type of oscillations set up.

The following method yields more practical results. Suppose a wavemeter circuit to be excited by an undamped e.m.f. of a certain radio frequency. When the variable condenser is adjusted to a value C_r that will produce resonance, the reactances of capacity and inductances are then equal.

$$X_L = X_C$$

$$\text{or} \quad wL = \frac{1}{wC_r}$$

For Resonance $\quad I_r^2 = \dfrac{E^2}{R^2}$

If the capacity C_r is changed to some value C

$$I_1^2 = \frac{E^2}{R^2+\left(wL - \frac{1}{wC}\right)^2} = \frac{E^2}{R^2+\left(\frac{1}{wC_r} - \frac{1}{wC}\right)^2}$$

$$\frac{I_r^2}{I_1^2} = \frac{R^2+\left(\frac{1}{wC_r}-\frac{1}{wC}\right)^2}{R^2} = \frac{1+\left(\frac{1}{C_r}-\frac{1}{C}\right)}{R^2 w^2}$$

$$\frac{I_r^2 - I_1^2}{I^2} = \frac{(C_r - C)^2}{(C_r C)^2 R^2 w^2}$$

$$\text{or} \quad R = \pm \frac{C_r - C}{C_r C w} \sqrt{\frac{I_1^2}{I_r^2 - I_1^2}}$$

The oscillatory current induced in the wavemeter or other oscillatory circuit will be damped due to the resistance R of the wavemeter circuit, and the logarithmic decrement δ_1 can be obtained

$$\text{since} \quad \delta_1 = \frac{R}{2fL} = \pi R w C_r$$

Substituting the value of R from equation (5) in $\pi R \omega C_r$

$$\delta_1 = \pm \pi \left(\frac{C_r - C}{C}\right) \sqrt{\frac{I_1^2}{I_r^2 - I_1^2}}$$

If the e.m.f., and hence the oscillation of the primary exciting circuit is slightly damped it will also have a logarithmic decrement δ_2, and Bjerknes' proved that the total decrement measured is the sum of these two values, or

$$\delta_1 + \delta_2 = \pm \pi \left(\frac{C_r - C}{C}\right) \sqrt{\frac{I_1^2}{I_r^2 - I_1^2}}$$

The right hand member of the equation holds very nearly true for this case. This formula is very nearly correct for three particular conditions; first, the coupling (See Chapter III for a discussion of coupling) between the wavemeter and exciting circuit must be very loose so that the oscillation of the secondary has almost no effect upon the primary; second, $\frac{C_r - C}{C}$ must be small, considerably less than 1; and third, the values δ_1 and δ_2 must be small, preferably not over .20.

To measure the logarithmic decrement of a wave or primary oscillating circuit with a wavemeter or other secondary oscillating circuit adjust the condenser to resonance as indicated by the hot wire ammeter in the wavemeter circuit, and note the value of I_r^2 for the capacity at resonance C_r. Change the capacity to C and note the resulting value of I_1^2, and if the value of δ_1 (for the wavemeter) is known the value of δ_2 may be easily calculated. If in the measurement C is adjusted so that I_1^2 is $\frac{1}{2} I_r^2$ the radical becomes equal to unity, simplifying the calculation.

The decremeter is simply a carefully designed wavemeter for which δ_1 is known, and it is sometimes constructed so that it is direct reading. If a hot wire galvanometer or thermocouple is connected in the decremeter circuit its deflections are proportional to the heating or current squared so that the readings do not have to be squared to use in the formula, equation (6). It may be well to mention that the ordinary D'Arsonval type or a dynamometer type ammeter or galvanometer cannot be used in radio frequency on account of the extremely high reactance of the coils, hence the hot wire or thermocouple types are resorted to. If a wavemeter used as a decremeter has its variable condenser calibrated to read directly in wave lengths (meters) the form of equation (6) can be changed to

$$\delta_1 + \delta_2 = \pm \pi \left(\frac{\lambda_r^2 - \lambda_1^2}{\lambda_r \lambda_1}\right) \sqrt{\frac{I_1^2}{I_r^2 - I_1^2}}$$

The student may verify this. The decremeter may also be used to measure the sharpness of resonance of an oscillating circuit, and high frequency resistance. Various methods are described in Bulletin #74, Bureau of Standards. See pages 38, 94 and 185. The Kolster decremeter used in the Bureau of Standards and the U. S. Navy is also described in this Bulletin.

CHAPTER II

ANTENNAS

I. The Simple Antenna.

Hertz found that two metal plates connected to a spark gap, and excited by an induction coil radiated waves when a discharge took place across the gap. This apparatus, as shown in Fig. 5 , is a simple oscillatory circuit having inductance and capacity, and it oscillates at its own natural frequency when the gap discharges. This apparatus radiates waves as does the primary condenser circuit of the Lodge experiment, but more efficiently due to the fact that the plates of the condenser are widely separated. The simplest form of antenna is shown in Fig. 6 . It consists of a single vertical wire AB connected through the spark gap S to the earth. The wire and the earth form the two plates of a condenser while the wire also has a certain amount of inductance. The induction coil C charges the wire to a sufficiently high voltage to cause a discharge across the gap. This form of oscillator oscillates due to its inductance and capacity and radiates waves whose length is $2\pi v\sqrt{LC}$ where L and C are for the antenna. It may be of interest to mention that this was Marconi's first transmitter using an antenna or "aerial".

Before considering antennas further it will be well to explain partially the nature of the radiated wave, but it must be borne in mind that this is not a complete explanation. The exact phenomena will be explained further in the Chapter on Electromagnetic Waves. Considering the single vertical wire oscillator or antenna of Fig.6 suppose the wire AB to be charged positively. Then electrostatic lines may be imagined to extend from the positive to the negative or from AB to earth as shown in Fig.7 . When discharge current flows from AB to earth circular magnetic lines of force $M, M^1, M_1, M_1{}^1$, etc. are set up having the direction as indicated. The discharge current decreases the electric strain, or number of electrostatic lines of force, and it will be noticed that the decrease of electric strain is accompanied by increase of magnetic field or strain, and conversely a subsequent decrease of magnetic field again produces an electric strain in the medium adjacent to it, but in the opposite direction, electric strain lines will be set up,

say at O. These lines again collapse setting up magnetic field, say at P. The wave set up is a propogating action and proceeds by successive increasing and decreasing adjacent electric and magnetic strains. (See Chapter on Electromagnetic Waves for more complete discussion). An electromagnetic wave proceeds, not by any physical vibration of the particles of ether, as air particles in a sound wave do, but by a periodic alteration of the electric and magnetic condition of the ether particles.

When the antenna is charged negatively due to the rush of current to the earth the disturbance set up will have traveled by the above process to a point H and the fields at point H at this instant will have the directions **shown**. When the antenna is again charged positively, or one cycle after the first discharge, the field set up by the first discharge will be at F, and will extend all around the antenna at this distance. The distance from the antenna to H is called a half wave length, and the distance from antenna to F, a full wave length. Similarly when a wave is progressing along the surface of water the distance from crest to crest is a full wave length, and the distance from one point of instantaneous zero displacement to the next, or the distance from crest to trough is a half wave length. These distances remain constant in an ether or electromagnetic wave just as they must do in a water wave. Fig.8 shows the relative positions of the electric and magnetic fields more clearly. In this Fig. part A shows the instaneous value of electric and magnetic fields in one direction. The electrostatic **lines** are supposed to extend up to the ionized or conducting layers of the atmosphere, known as the "Heaviside layer". The dots represent the distribution of the magnetic lines at right angles to the electrostatic lines, and their relative locations at the same instant. Part B is a curve showing the variation of electrostatic field with distance from the antenna, and is assumed to vary as a sine wave. Part C shows the position of magnetic field at the same instant. The page may be folded at DE so that FEG is a right angle and the relative directions of the instaneous value of the two fields may be better understood. It must be remembered that part A is an instantaneous picture, and B and C show instantaneous values of the electrostatic and magnetic fields. These fields are progressing outwards and one quarter cycle later the position of maximum electric and magnetic fields will have just changed places. Comparing again with a water wave one may imagine the crests and troughs to represent the maximum positive and negative electric fields, and the points of zero displacement to represent the maximum magnetic fields. This illustrated by Fig.9 A, C, and E are the troughs and crests (maximum electric fields) and B, D, and F are points of zero displacement, but of maximum rate of motion. The directions of motion of B, D, and E alternate. Likewise the adjacent maximum magnetic fields are opposite in direction. Now as the wave progresses points A and B move in the direction of progress, but the particles of water have only vertical motion, it is only the displacement that progresses. Considering again the electromagnetic wave the points maximum

positive and negative, fields may be considered as progressing outwards, see Fig. 8, as do the points of maximum magnetic fields. (The directions of adjacent maximum magnetic fields alternate in and out perpendicular to the page if the direction of the electric fields are in the plane of the page as shown).

II. Constants of Antennas.

A Hertzian oscillator may be made of two rods terminating in a sphere gap as shown in Fig. 10. If this oscillator discharges, the portions near the gap will carry a heavy maximum current while the portions near the outer ends of the rods will have a very little current. The reason for this distribution of current will be clear when it is remembered that the portions at the spark gap carry the charging or discharging current for the entire "rod condenser" while the portions at the outer ends carry only the charging current for those parts. The dotted line, then, represents the distribution of current along the rods of the oscillator. When the oscillator is charged and the current is zero the positive charges accumulate on one rod, and the negative charges on the other, but at the gap the positive and negative charges near each other are neutralized so that the potential is zero, and the farther along the rod toward its outer end the less the neutralized effect, and hence the greater the potential. The full line wave represents the distribution of potential along the rods when it is fully charged and the current is zero. These are often called stationary waves. The term is misleading in a sense because the current and potential are not constant or stationary but vary. Fig. 11 represents the current and potential at various instants. It can be shown mathematically that for such an oscillator $i = 2a\sqrt{\frac{C}{L}}\cos Bx$, (See Fleming p. 337-370) where a is a constant, B is $\frac{2\pi}{\lambda}$ and x is the distance from the center or gap outward toward one end. From the above discussion the current is zero at the outer end or $i = 0$ when $x = l$ in Fig.
Then

$$\cos Bl = 0, \quad \text{or} \quad Bl = \frac{\pi}{2}$$

$$\frac{2\pi l}{\lambda} = \frac{\pi}{2}$$

$$l = \frac{\lambda}{4}$$

Hence for a linear or rod oscillator the frequency of the oscillatory current is such that the emitted wave length is four times the length of one rod.

The single vertical wire antenna connected through a gap to earth is very similar to the oscillator discussed, and the wave length of the wave emitted when the antenna oscillates is approximately four times the vertical length. This relation

varies somewhat for different shapes of antennas. The frequency and wave length depend upon the inductance and capacity in a condenser circuit, and since a vertical antenna has both of these qualities, its wave length will depend upon them. Connecting inductance in series will increase the total inductance of the oscillating current and since $\lambda = 2\pi v \sqrt{LC}$, λ is increased. Connecting capacity in series with the antenna near the gap decreases the total capacity, and hence decreases the wave length. Fig.13 shows the maximum current and voltage distribution for these cases. When inductance is connected in series the antenna is said to be "loaded". The antenna approximates closely the simple form of capacity - inductance oscillating circuit, and if the resistance is low $\lambda = 2\pi v \sqrt{LC}$ also holds. Since the spark gap introduces resistance into the antenna, and makes the decrement of the emitted wave very high, the gap is omitted and the antenna is caused to oscillate by coupling it inductively to a condenser circuit having a spark gap in series. This will be described fully in Chapter III.

The form of antenna discussed above is not practical for radiating strong fields. One simple reason is that it is desirable to have a large discharge current and since $I_o = w\ C\ E_o$ C must be large. This is accomplished by constructing the antenna in one of the forms as shown in Fig.12. For these types the wave length is not equal to 4 l, although in the case of the "L" type $\lambda = 4.7$ l very roughly. The greater the area covered by the flat portion the greater the capacity, and hence the greater the wave length. The inductance is decreased when the area is increased, but not as fast as the increase in capacity. For reasons shown in Chapter VI the height of the flat topped portion must be as great as possible hence it is not permissible to construct a low antenna so as to gain capacity. The inductance and capacity of the various forms of antennae can be calculated approximately from formulae given in various hand books, or Bulletin No. 74 Bureau of Standards, and the wave length predetermined.

The efficiency of an antenna depends upon its resistance in a particular manner. The energy consumed by the antenna may be taken as $I^2 R_a$ where R_a is the total resistance of the antenna. This is made up of three parts; that due to ohmic resistance of the wires at radio frequencies, (R), a resistance that represents the energy lost due to leakage, or brush discharge, (R_1), and an equivalent resistance that represents the amount of energy radiated, (R_z). The total energy given to the antenna is then $I^2(R + R_1 + R_z)$. $I^2 R_z$ then is the energy stored in the magnetic field around the antenna when it oscillates, and is the useful energy in transmission. R_z varies as the square of the height, and inversely as the wave length. Formulae have been worked out for R_z and are given in Zenneck. In this treatise the actual radiated field and received current will be dwelt on at length in place of the radiation resistance. In a well designed antenna R_z must be high, and R and R_1 must be low.

III. Directive Properties of Antennas.

A study of the nature of the fields set up, and of the direction of propogation (See Fig. 8) will show that this direction is at right angles to the path of the discharge current and the direction of the electrostatic strain. Hence no field is radiated off the end of the vertical wire in the direction of the wire. If this wire is very long and is bent over near the earth as shown in Fig.14 an exaggerated "L" type antenna is formed and there is very little radiation in the direction A B. The strongest radiation will be in the direction of the arrow P. All "L" type antennas are more or less directional, the greater the length A B in proportion to the vertical height, the more directional it is.

The Bellini Tosi antenna is very directional due to its peculiar construction. The directional property of this antenna is due to the reinforcement of fields set up at different points. The currents in different portions are not in phase and the two parts of the antenna are separated. Hence the fields set up are due to addition of alternating strains not in phase. This is more or less true of all large types of antennas. The construction of the Bellini Tosi type is shown in Fig.15. The plane of this antenna is the plane of the paper. At some point P in the plane of the paper the fields due to the oscillations in the upright wires adding directly. The oscillations in these two portions are opposite in phase but due to their space separation of about $\frac{\lambda}{2}$ the fields created by the upright wires will be 360° out of phase or add directly. Usually the distance between wires is made somewhat less than $\frac{\lambda}{2}$. At a point opposite the center of the antenna and on a line perpendicular to the plane of the antenna the fields will arrive simultaneously from both upright wires but they are 180° out of phase and will neutralize. The antenna, then is directional in either direction in the plane of the paper. A very good discussion of this type is found in Zenneck pages 345 - 362. This type of antenna is mentioned because it has come into practical commercial use recently. The Alexanderson Barrage receiver described in the last Chapter makes use of this type.

IV. The Loop Antenna.

The three general classes of radiators are the open antenna, such as the vertical type, or "L" type, the condenser type (Lodge Experiment) and the loop. The loop antenna consists of several turns of wire wound on a wooden, or other insulating frame, the wires being separated from each other to reduce the self or distributed capacity of the loop. The loop may be square, rectangular, or circular. Each loop has a certain natural wave length depending upon its inductance and capacity;

which obviously depends upon its area, the number of turns and spacing of wires. Tables are given on p. 60, Radio Amateur News, August 1919, showing the proper dimensions of loops for sending and receiving on various wave lengths. For a wave length of 2500 meters the best size of loop to use is one having 25 to 30 turns of wire wound on a frame about six feet square, the wires spaced one-half inch apart.

Fig. 16 shows a loop arranged to generate electric waves by the oscillatory action of the condenser charge. Fields are set up and radiated just as in the case of the vertical antenna, but there is one important modification. When the current flows up the side B it flows down the side C D and if A B and C D are very close together the radiated fields set up by each side will reach P at the same time and since they are opposite in sense the resultant field at P will be zero. If the coil is made larger so that A B and C D are farther apart the fields due to each arrive at P slightly out of phase and the resultant and field at P is equal to the vector difference. If the dimension W of the loop is made equal to $\frac{\lambda}{2}$ the fields at P due to each will add. In practice this condition cannot be obtained because as W is increased the inductance and hence λ of the radiated wave are increased. A comparatively strong radiated field must be obtained by making the discharge current very heavy, and the loop as large as practicable. In the case of a loop radiator the radiation is strongest in both directions parallel to the surface of the earth, and in the plane of the loop, and zero in directions perpendicular to this plane. The reason for this is that the opposite fields due to current in A B and C D reach any point in the axis of the loop at the same time and are neutralized. The variation in intensity of radiated field from a loop is shown by Fig. 17. The loop can be used for receiving as well as for transmission, and the directive property is the same, i.e. for maximum strength of signals the loop must be set with its plane in the direction of the transmitting station. It is obvious that such a loop could be used to determine the direction of a particular transmitting station if the loop is arranged to turn on a vertical axis. One important application is in the aeroplane direction finder described in Chapter VIII.

V. Commercial Antenna.

The representative types of antennas are found in those used by the U. S. Navy, U. S. Army, ships, and some of the High Power Commercial Stations.

The Standard antenna of the U. S. Navy high power stations consists of three flat topped aerials swung between three towers set at the corners of an equilateral triangle. The scheme is shown by Fig. 18, which is a plan view. The Navy Stations at Annapolis, Arlington, Va., San Diego, and Cavite, P. I. use this type of antenna. The antenna system in the Arlington Station is inclined, as two of the towers are 450 ft.

high, and the third 600 ft.

The U. S. Army has adopted as standard the "L" type antenna for its permanent stations at various department headquarters. For field use the umbrella form is used, as it is the most quickly erected and dismantled, and has considerable capacity. Loop antennas are also being developed by the Signal Corps.

Ship antennas are usually of the L or T type, the T type having the advantage that it is not so directional, but it has a shorter wave length than an L type and requires more inductance in series with it to transmit on 600 meters. Ships are often arranged to transmit on 3 wave lengths, 300, 450, and 600 meters, hence the antenna should have a natural wave length of about 280 meters, and for 600 meter transmission must be "loaded" with considerable inductance.

The Marconi trans-Pacific Stations use a very long L type antenna which is very directional. These antennas are two miles long, and the flat top is 450 ft. above the earth. The wave length used is 17000 meters. These stations are used for communication between the United States and Japan. A relay station is located at Kahuku, Hawaii. These stations are discussed in Chapter VIII.

VI. Atmospheric Strays.

All who have listened at a receiving station have noticed the effect of strays or "static" in the receivers. Various noises are heard, rattling, frying noises, clicking noises, and loud crashes are noticed at different times. The exact nature of strays has been the subject of much study and research. Whatever their origin, it seems to be pretty well established that what we hear as a stray is the result of a discharge of the antenna due to a charge induced upon it by some means such as induction from a passing cloud; or the discharge of a cloud. Dr. De Groot (Proc. I. R. E. 1917) has attributed some of the strays to charges induced in the antenna by the "cosmic" particles of dust which he says strike the earth's atmosphere as it travels through space. Weagant (Proc. I. R. E. June 1919) has shown that most of the strays are propogated vertically downward, and that the discharge due to the stray has a frequency determined by the L and C of the antenna and receiving circuit, and therefore cannot be tuned out. Weagant has perfected successful circuits for eliminating strays. One of these is described in Chapter VIII.

The intensity of strays varies greatly. Strays are comparatively strong during the day and early evening, and decrease to a low value near midnight during clear weather. This is explained as due to ionization of the rarified upper layers of air by the ultra violet rays of the sun. This also reduces the strength of transmitted signals so that strays are

lower and signals are stronger at night. A series of observations on strays are described in De Groot's paper cited above. Strays are more intense in summer than in winter, more intense in the Tropics than in temperate zones, and are very bad just preceding and during a thunder storm. At present strays limit the "commercial range" of a station to about one-tenth of the range possible if strays were not present. The intensity of strays varies greatly with the type of antenna. The greater the height and capacity the greater the intensity. Low antennas are more free from strays than high ones, but the signal strength is lower also. Receiving antennas have been constructed in many forms such as double antennas, ground antennas, directional systems, etc. in an attempt to reduce or eliminate strays. Most attempts so far have been unsuccessful due to the fact that any modification which reduced the intensity of the stray also reduced the signal in the same proportion. This is particularly true of all so called anti static balanced receivers. Weagant's static eliminator is the first successful device as it reduces strays to a negligible value while actually increasing the signal strength fifty per cent. This device will be described in Chapter VIII. A recent successful device is the Taylor balance system using wires under ground and on the surface. This is described in the Proc. I. R. E. December, 1919.

CHAPTER III

THE DAMPED RADIO TRANSMITTER

I. Properties of Transmitters.

If an antenna is connected through a spark gap to earth and excited by means of an induction coil connected as in Fig. 6 the antenna will discharge sending out electromagnetic waves. However, as was pointed out, the logarithmic decrement is very high and the transmitter inefficient. A more efficient form of transmitter is shown in Fig. 19 The transmitting condenser C is charged by the induction coil I so that the gap breaks down and the charge moves back and forth in the manner of damped oscillatory discharge through the primary of the "oscillation transformer". This induces electromotive forces in the "open oscillatory circuit" which causes it to oscillate at the same frequency and wave length as the primary or closed oscillatory circuit. If S is adjusted so that the open oscillatory has the same natural period as the closed resonance is obtained and the current flowing back and forth from antenna to earth is a maximum. The hot wire ammeter H. W. indicates this condition. If an induction coil is used to charge the condenser C the highest e.m.f. is generated on the "break" of the interrupter and the discharge of the condenser occurs at about this instant. If a transformer and a.c. supply is used the discharge occurs at the peak of each positive and negative half wave and the curve of e.m.f. at the condenser is as shown in Fig. 20 The number of discharges per second is called the discharge frequency or wave train frequency and is seen to be twice the frequency of the A. C. supply. It must be remembered that the frequency of oscillation is independent of this frequency and depends only upon the L and C of the oscillatory circuit. In Fig. 20 T_s represents the time required for one cycle of the A. C. supply e.m.f., or time required for two wave trains to be emitted, while T_o represents the time for one complete oscillation of the closed and open oscillatory circuits.

The reasons why the form of transmitter described above is not efficient will be made clear by a discussion of the actions in the closed and open oscillatory circuits. These will be referred to as the primary and secondary, respectively.

The damped oscillation of the primary begins at A Fig. 21 and dies out (due to the resistance) at t_1. As soon as the oscillation starts in the primary voltages are induced in the secondary and an oscillatory current gradually builds up in

the latter starting at B until at t_1 when the oscillation in the primary is zero, that in the secondary will fall off because the induced e.m.f. in the secondary is zero. Hence when the oscillation in the primary is zero that in the secondary has reached its maximum. Now the oscillation in the secondary begins to fall off, and in so doing builds up an induced oscillation in the primary. The ionized condition of the air between the electrodes of the gap allows the secondary to keep up oscillation in the primary and the result is as shown in Fig. 21 Thus a kind of beat phenomena is set up, which of course means a loss of energy. Also it will be noticed that the oscillations in the secondary, and hence the radiated wave length will be very highly damped. If the coupling is made loose the transfer of energy back and forth is less rapid due to the weaker effect of the primary upon the secondary, and hence longer time required for absorption of the energy of the primary by the secondary (this corresponds to lower decrement). Furthermore the radiated wave will have two frequencies, both of which are different from the frequency to which the primary and secondary circuits, Fig. 19 are tuned. The reason for this is that when P and S are coupled closely the frequency of oscillation of the closed or primary circuit will depend upon the inductance, which is M L_p where M is the coefficient of the coupling. So it would require a readjustment of the inductances and capacities of primary and secondary to obtain resonance with close coupling. But even then the antenna would radiate two frequencies. The reason for this can be seen from an inspection of Fig. 21. Since the currents A and B of primary are 90° out of phase, part of the time both currents will be positive simultaneously and part of the time they will be opposite in direction at the same instant, they change direction relatively every one quarter cycle. Therefore the magneto motive forces in the oscillation transformer coils P&S, Fig. 19 will aid and oppose every one quarter cycle resulting in a varying field through these coils, and hence a varying inductance of each circuit. Thus the frequencies of the oscillations change every one quarter cycle, and two distinctly different frequencies and wave lengths are radiated. The closer the coupling the greater the strengthening and weakening of the field, the greater the change in inductance, and the more different the radiated wave lengths. If a wavemeter with its condenser scale calibrated in wave lengths be coupled inductively to the antenna of Fig. 19 the variation of current with condenser setting is shown by curve A, Fig. 22. The abscissae for the two points of maximum are the wave lengths of the emitted waves. If the coupling be made closer curve B will result. These resonant frequencies can be solved for thus: A, Fig. 23 represents two oscillatory circuits directly coupled by inductance M. The circuit is considered to be open at E and the expression for the total impedance at E obtained. Since the impedance of a circuit at resonant frequency is zero (zero resistance) the expression is equated to zero and F_1, one resonant frequency is solved for. The same is done for the circuit at G. This solution contains complex

algebra but the principle is simple, it is outlined on pages 52 - 59, Bulletin No. 74. When the coupling is inductive, as in B, Fig.23 , and if the natural frequencies of the two circuits are the same when not coupled, i.e. $f_1 = f_2 = f$.

$$f_1 = \frac{f}{\sqrt{1+K}} \quad \text{and} \quad f_2 = \frac{f}{\sqrt{1-K}}$$

F_1 and F_2 are the two radiated frequencies (see Fig. 22). K is the coefficient of coupling and is defined as

$$K = \frac{M}{\sqrt{L_1 L_2}}$$

where M is the mutual inductance. When a transmitter emits two wave lengths energy is wasted, the transmitter interferes with others, and it is impossible for a receiving station to tune sharply to the incoming waves. Curve C, Fig. 22 is the ideal condition, a single wave length, and resonance in the wavemeter is very sharp. The remainder of this section is a discussion of means of attaining the end sought for.

II. Quenching.

Suppose that the oscillation in the primary of an inductively coupled transmitter be quickly suppressed or "quenched". The result would be as shown in Fig.24 . A represents the current in the primary. The current in the secondary builds up until it reaches a maximum at t, and, as there is no gap, and no high resistance in the secondary it oscillates freely, and at its own wave length, and the decrement is much lower as no energy is lost in a retransfer to the primary. This persistent wave gives efficient radiation, because of its longer duration, and hence an increased amount of time utilized in producing waves for each condenser discharge in the primary.

There are several ways of obtaining the quenching desired. One of the most successful methods is by means of what is known as the quenched gap, and is shown in Fig.25 . It consists of a series of copper plates separated by mica washers .01 inch thick. The discharge travels from one plate to another across the minute gaps in series crossing from five to fifteen gaps in series. The gap space within the plates is a partial vacuum. This gap has the property of quenching the primary oscillation very quickly, and since the resistance is very high when the oscillation dies down the secondary will oscillate freely as shown in Fig.24 . When this gap is used the discharge in the primary occurs on or near the peak of the wave of the power transformer e.m.f. as shown in Fig.20 . The tone that is heard in the receivers is the number of discharges per second of the primary and for good reception through strays must be about 1000 per second, hence the supply frequency must be 500 cycles. This frequency is very common in commercial practice.

Another method of securing quenching is to use a gap with moving electrodes. This is called a rotary gap and is illustrated in Fig.26 . If this gap has the proper number of electrodes on its wheel, and is mounted on the shaft of the alternator which generates the A. C. supply at 500 cycles the discharges may be arranged to always take place on the peak of the supply wave as the moving and stationary electrodes will be opposite at this instant. This is called a synchronous rotary gap. If the wheel of the gap is driven at varying speeds by a separate motor the discharge takes place at various points on the e.m.f. wave. This is known as a non synchronous gap. Quenching is obtained with this gap, however, the tone is usually not so smooth as with a quenched gap or synchronous rotary gap. If a non synchronous gap is used the frequency of the supply may be low, say 60 cycles, and the discharge or wave train frequency will depend upon the speed of the gap and number of electrodes. The discharge frequency for any rotary gap equals the number of electrodes on the disk multiplied by the revolutions per second of the wheel. It was found at Washington University that for the smoothest tone the discharge frequency should be an odd multiple of the primary frequency. Some writers disagree with this. It has also been found that if a rotary gap is made with 4 or 6 gaps in series the quenching is improved, the wave sharper, and tone purer.

Other types of quenched gaps are in use and are quite successful, some consist of stationary tungsten electrodes about .004 inch apart in a vapor of alcohol, or a stationary and rotating plate about 1/64 inch apart, or stationary gaps with blowers attached. Some of these will be described later.

III. Features of Transmitting Apparatus.

By discharging a condenser in the primary circuit it was shown that a more persistent wave will be radiated by the coupled antenna circuit. Also the energy radiated in this system is much greater than were possible if the antenna were charged directly from the power, or charging transformer. The condenser in the primary oscillatory circuit can be made with relatively large capacity, and thus a large quantity of energy is stored in the condenser ($\frac{1}{2}$ C E^2), and on discharge is stored in the magnetic field about the inductance ($\frac{1}{2}$ L I^2). The oscillation in the secondary builds up as the primary dies down, as was already explained, thus the energy is gradually transferred into the antenna while it is oscillating at resonance and maximum current.

The capacity of the condenser required to store the energy is easily obtained:

From the relation

$$W = \frac{1}{2} C E^2 \text{ Joules,}$$

if the condenser is charged once per second,

for Watts = joules per second

If the condenser is charged N times per second

$$W = \frac{1}{2} N C E^2 \text{ watts}$$

$$\text{or} \quad C = \frac{2 W 10^6}{N E^2} \text{ microfarads} \qquad (8)$$

where N is the frequency of supply

This is also the discharge frequency, or number of wave trains per second

$$N = \frac{1}{T_s}$$

E = charging voltage or secondary voltage of supply transformer.

If the capacity of the power or supply transformer is 1 K. W., its voltage 20,000 volts and the discharge frequency 1000 cycles

$$C = \frac{2 \times 1000 \times 10^6}{1000 \times (20,000)^2} = \frac{10^6}{2 \times 10^8} = .005 \text{ m.f.}$$

If the discharge frequency is 500 C must be .01 m.f. If a 1 K. W. transmitter is to be built and the wave length is to be 200 meters this latter is the maximum capacity that can be used because the shortest possible conductors are required to keep the wave length of the primary within this value. If higher spark or discharge frequency is used a lower capacity may be used for the same capacity of transmitter. The energy may also be increased by increasing the transformer voltage, but it is not practicable to do this beyond certain limits on account of difficulties in insulation. Most commercial stations use between 5000 and 10,000 volts. The power or transmitting condenser in commercial apparatus is either glass plate in oil,moulded insulation, or compressed air type. For high power stations this latter type is most used. This condenser is made of many metal plates separated by air under high pressure, about 250# per. sq. in. It is very similar in principle to the variable air condenser used in the laboratory. The plates are about 1/8" apart, and at this high pressure stand more than 5000 volts without sparking across. No repairs are necessary on this

type of condenser in case of break down as is required in the case of a glass plate condenser.

The transformer used to charge the primary condenser should have an output which is equal to the power used in calculating the capacity of the condenser. This transformer should have large magnetic leakage which gives it poor regulation, and protects the windings from high frequency surges. The secondary voltage is often variable by means of taps or by a variable air gap in the iron core. In some commercial transmitters with a supply frequency of about 500 cycles the secondary of the supply transformer is connected across the condenser and the reactance of the former and capacity of the latter are of such a value as to provide a resonant circuit at 500 cycles. This results in a higher voltage drop across the condenser than the open circuit voltage of the transformer. These are called resonance transformers.

The primary or closed oscillatory circuit discussed carries a heavy current, and must have heavy conductors due to the skin effect of the high frequency oscillations. For a 1 K. W. set the primary oscillating current may be as much as 25 amperes while that in the secondary may be only 5 or 6 amperes. However, the wires in the antenna should be fairly large in order that the decrement of the radiated wave be low. For a 1 K. W. transmitter the antenna wires, if four or more be used, should be of 7-strand No. 22 phosphor bronze, the lead in and ground wires No. 6 stranded, or No. 4 solid copper.

The primary and secondary coils of the oscillation transformer are made in various forms, the flat spiral forms are most used for low power stations and the solonoidal forms for high power stations. Copper strip is usually used for the spiral forms.

IV. General Classes of Low Power Transmitters.

Commercial low power transmitters are divided into two classes, known as "impulse" or "beat" transmitters, and as "shock" or "impact" transmitters. The transmitter using the quenched or rotary gap described in the preceding articles is known as the impulse transmitter from the nature of the primary and secondary oscillations see Fig. 24 . It should be noted that the oscillation in the primary consists of from one to three complete cycles. If a gap such as the one with tungsten electrodes in alcohol vapor is used and properly adjusted the oscillation in the primary is reduced to less than one half cycle. This is known as shock or impact excitation. Fig. 27 shows this type of oscillations. In this system the primary discharge current is very heavy, and the coupling close. A description is given by the aid of a stereoptican of a representative type of each class.

Sometimes the quenched gap is shunted by a large capacity or capacities so that this local circuit is set in resonance and adjusts the frequency of the discharge to its own natural frequency. Fig. 28 shows a direct current tone circuit transmitter.

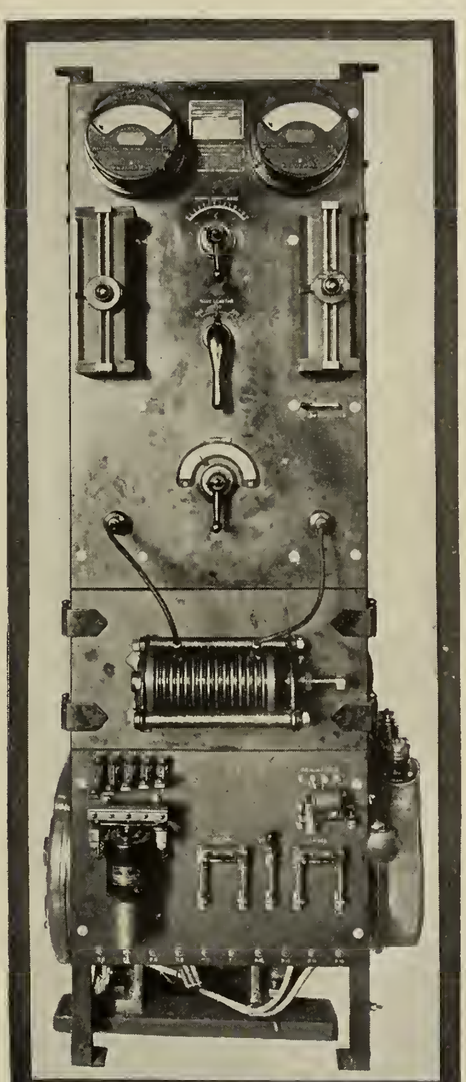
The power condenser P. C. is charged by a battery, a d.c. generator, or an alternator, 500 - 1000 volts. When the gap G breaks down P. C. discharges and the voltage impressed upon it decreases momentarily due to choke coils C. C. The frequency of the oscillation in the antenna is determined by the inductance of L and the capacity of P. C., but the wave train or discharge frequency is equal to the natural frequency of C_t, L_t and G in series. This is the "tone circuit". The French government has successfully used this type of transmitter using 20,000 volt d.c. generators for excitation. The low power transmitter using a tone circuit and Chaffee Gap has been successfully used as connected in Fig. 28 . A description of this gap is to be found in the Proc. I. R. E., August, 1916. Impact transmitters using this gap and circuit will be described later.

V. Description of Representative Commercial Type of Each Class.

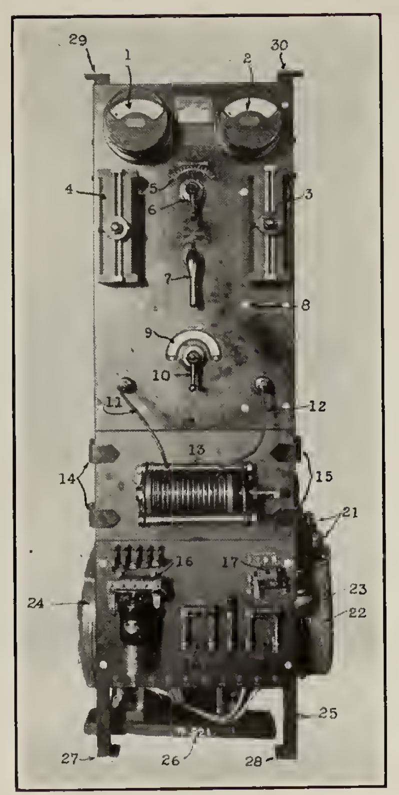
In order to give the student some idea of present day practice in commercial Radio Engineering one representative type of quenched gap tuned primary transmitter should be studied. The Marconi standard 2 K. W. 500 cycle panel transmitter for use on shipboard is of this type, and is shown in the cut next to this page. All the necessary apparatus for transmitting, except the key, is mounted either in front of or behind the panel. The transmitter is arranged to operate on three wave lengths, 300, 450, and 600 meters. To change wave length the operator merely operates the wave length changing switch shown on the center line of the panel about one-third of the way from the top to the bottom. The operating key, a small single pole switch for starting the motor generator, the antenna switch, and the receiving apparatus are placed on the operating table with the transmitter panel located conveniently at the operators right. The complete description of this transmitter cannot be taken up here for want of space but the student should read the description given in the article "Recent Standard Radio Sets" by Harry Shoemaker, Proc. I. R. E., August, 1916.

Writers note: An illustrated lecture is given on this transmitter covering most of the material included in the above paper.

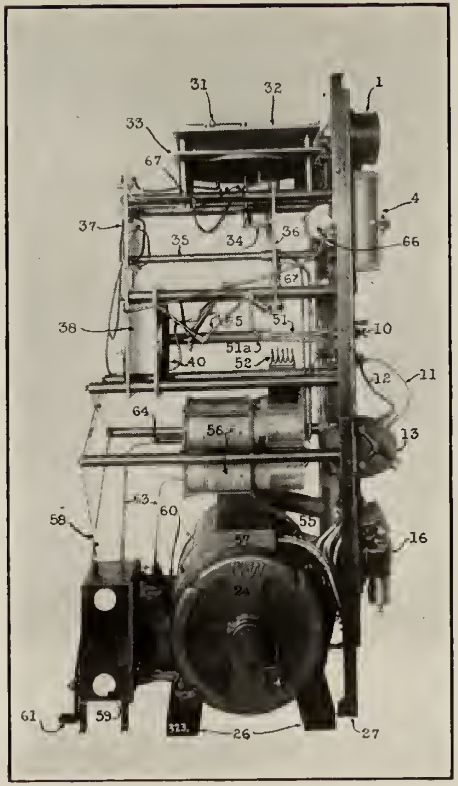
One type of impact transmitter is that manufactured by the Cutting and Washington Radio Corporation. Cuts of this apparatus are shown opposite this page. The first cut shows the transmitter panel, in front of and back of which are mounted the Chaffee gap, primary condenser, transformer, primary and



[redacted]. 1—Front view of the complete transmitter in the new Marconi standard 2 k.w. 500 cycle panel set



[redacted] 1



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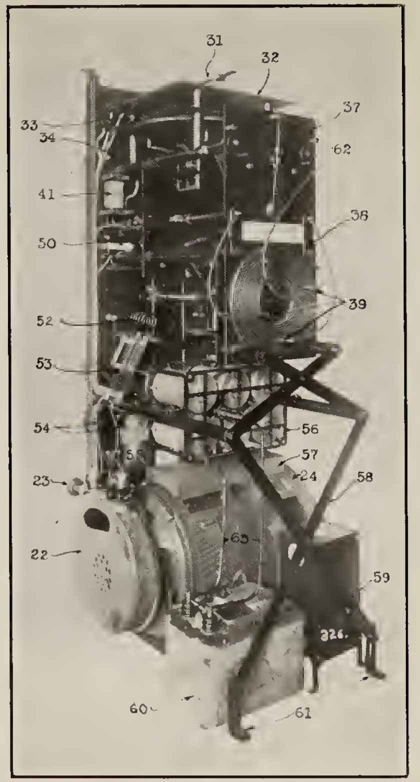
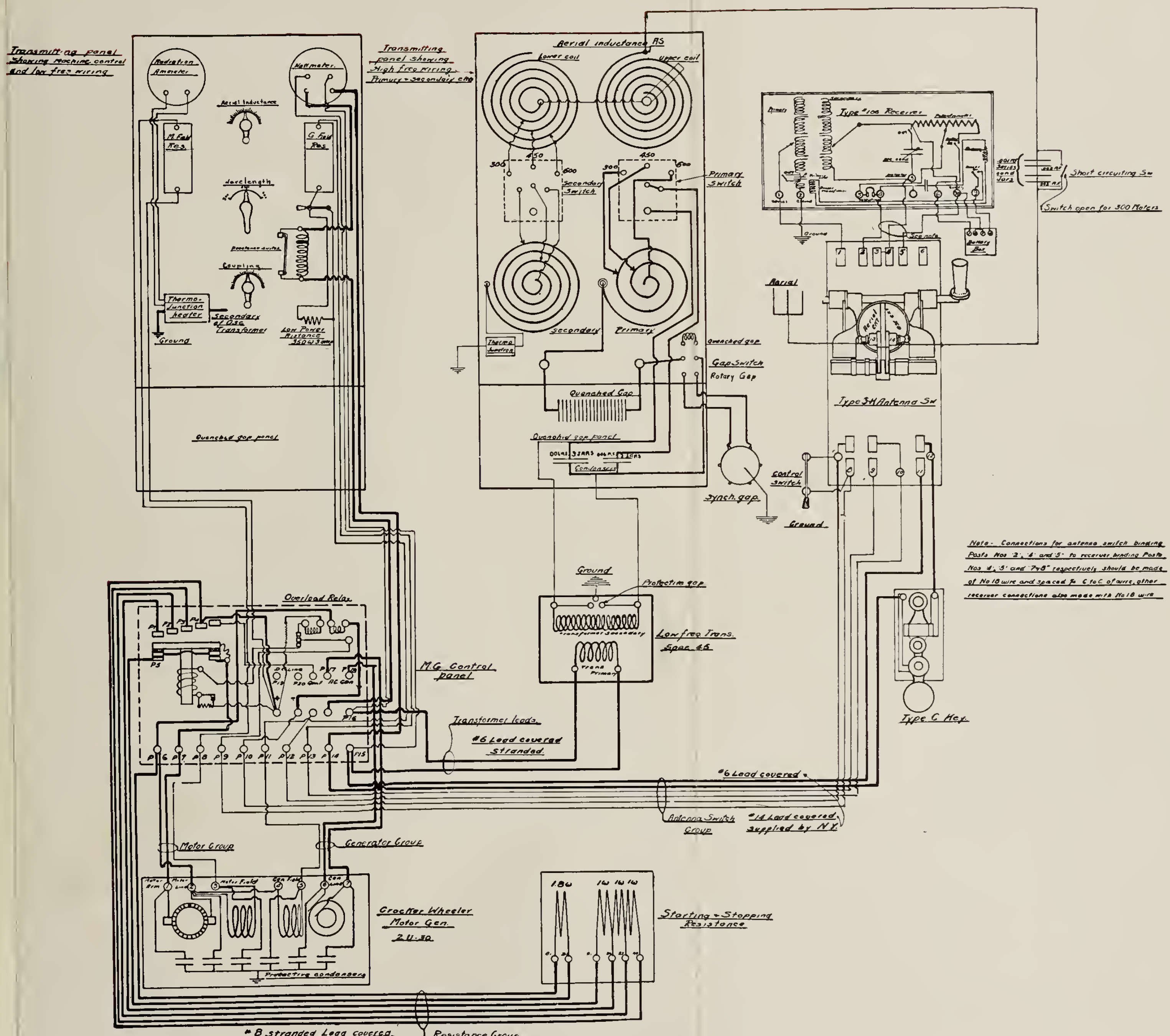


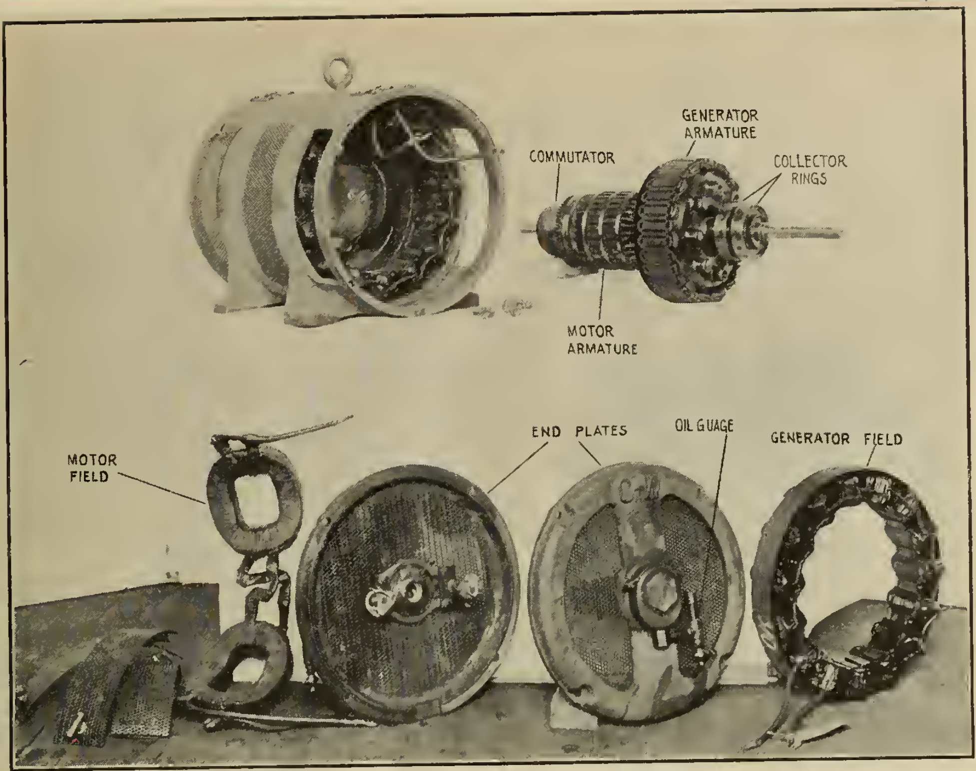
[redacted] 3

Views of Marconi 2K.W. Set.

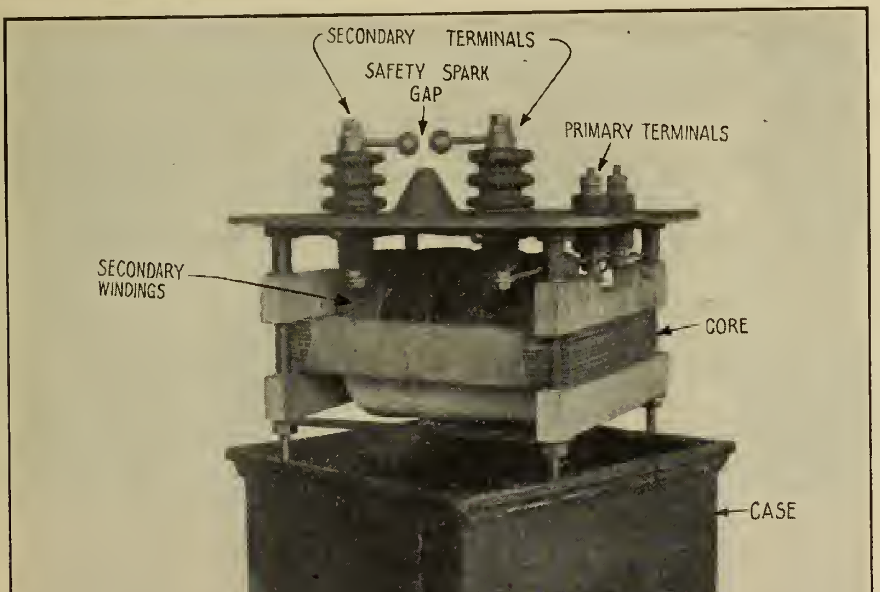
For explanation see Proc. I.R.E. August 1916, P. 318.



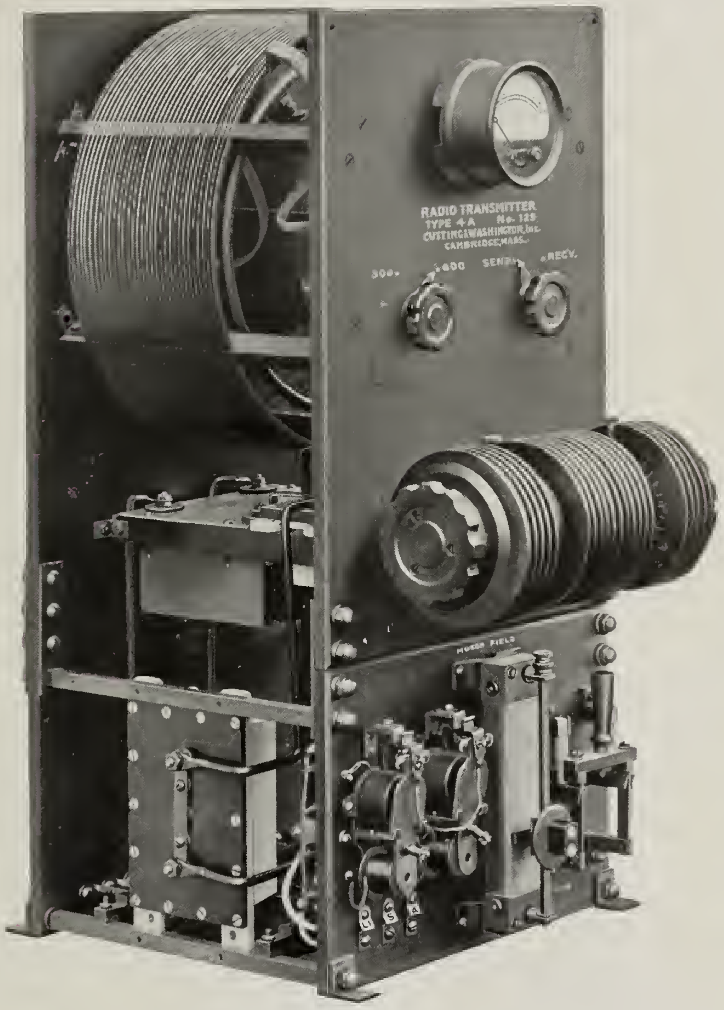
[redacted]—Connections of 2-Kilowatt Set



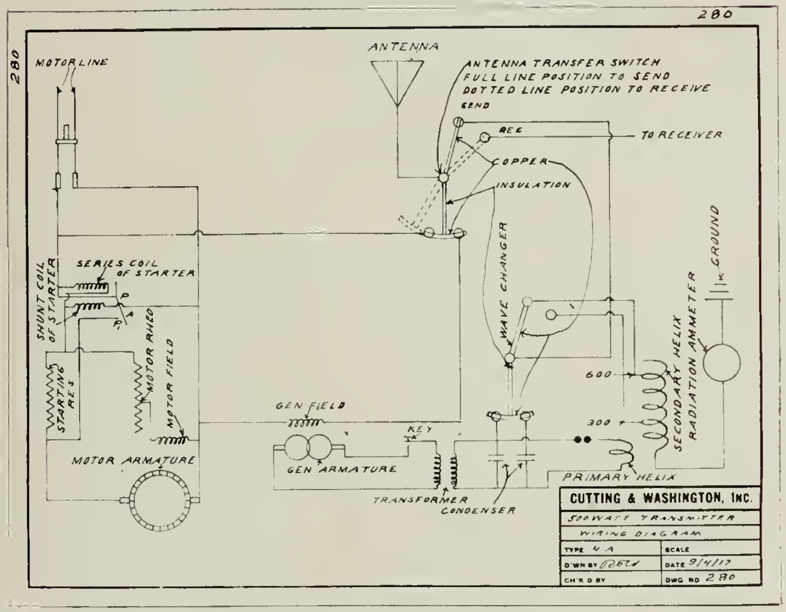
[redacted].—*Showing the general details of the Crocker Wheeler 2 K. W. 500 cycle motor-generator of the type used in modern Marconi radio sets. A two-pole direct current motor, taking current at 110 volts' pressure, drives a 2 K.W. 500 cycle alternating current generator. The armature revolves at 2,000 R.P.M. and the alternator delivers current on open circuit at an E.M.F. of 380 volts. When the armature circuit is closed the voltage drops to approximately 120 volts. The motor is designed to operate at a constant speed on D.C. voltages varying from 95 to 115 volts*



[redacted].—*Showing the construction of the Marconi 2 K.W. 500 cycle closed core transformer. The primary and secondary windings are wound on a special leg inside a rectangular iron frame. The transformer takes current at a pressure of 120 volts at the primary and delivers current at pressure of 12,500 volts at the secondary. The core is mounted on wooden blocks and the entire core and coils are immersed in a semi-liquid grease in a metal container. A safety gap is provided to prevent breakdown of the secondard windings under special strain. Both this transformer and the one shown in Figure 64 are specially designed for Marconi quenched spark transmitters*

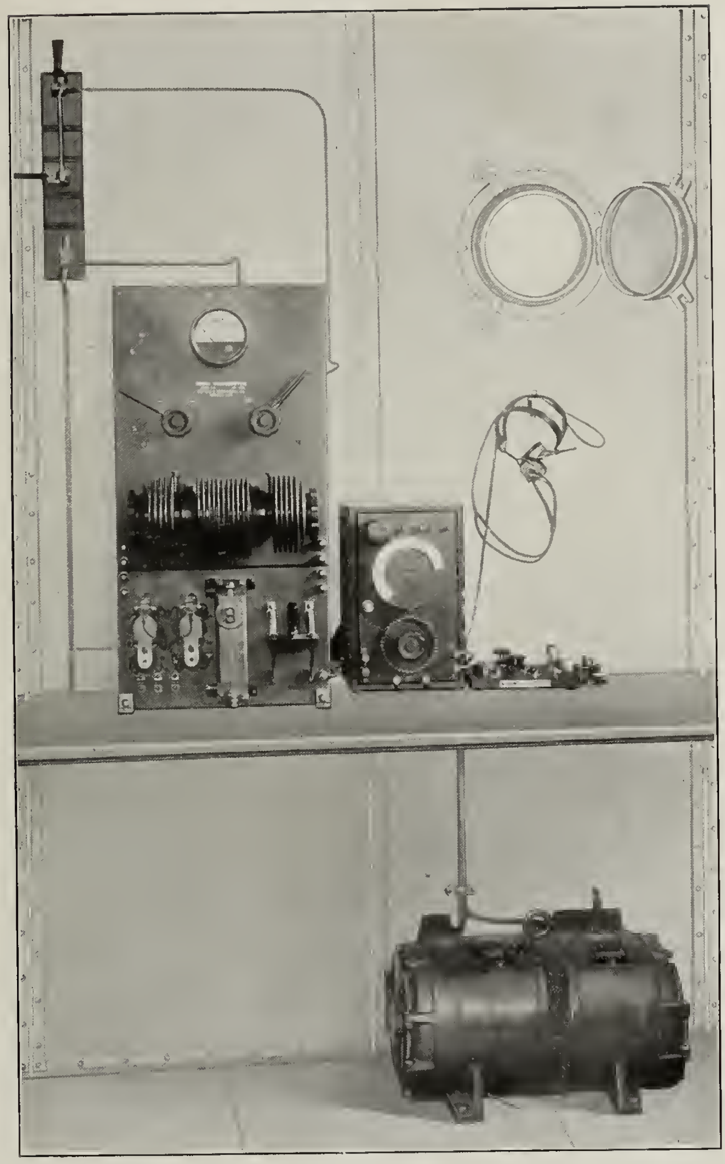


½ KW Transmitting Set — front view

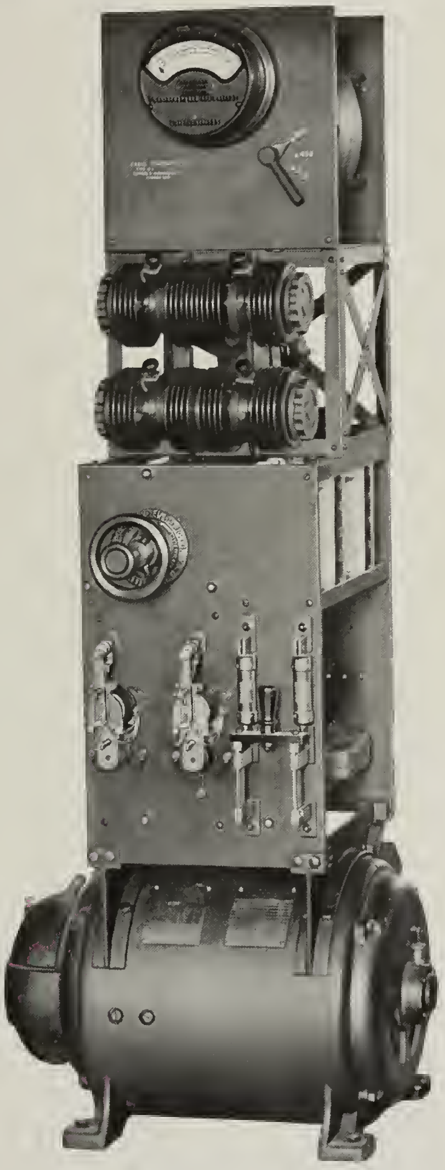


[redacted]

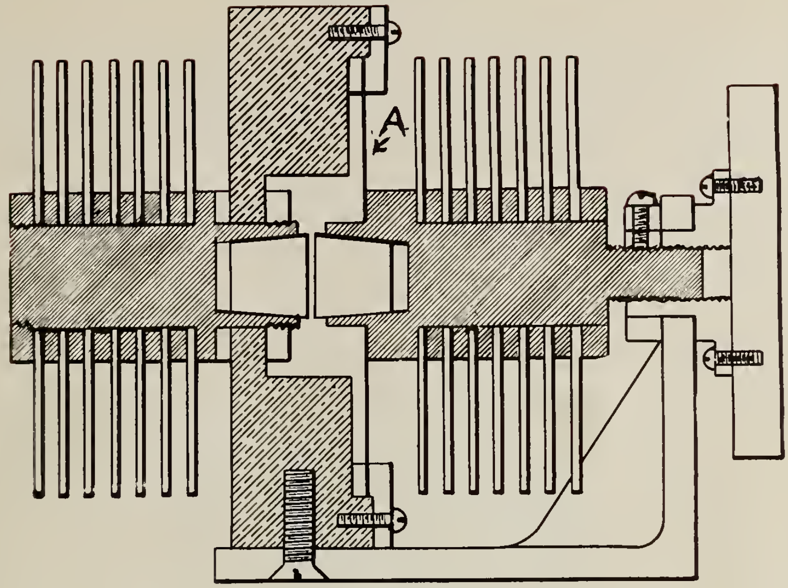
Diagram of Connections



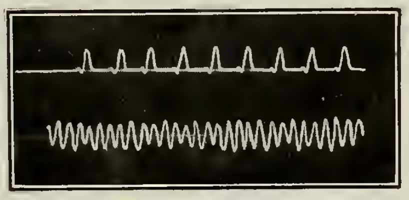
Complete Cutting & Washington ½ KW set installed on boat—
C & W sets can be operated by anyone who knows the code



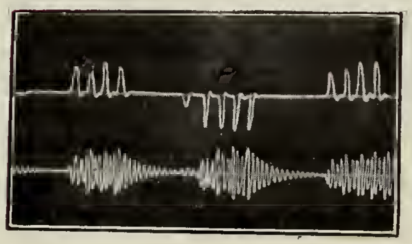
2K Transmitting Set
Dimensions: Height, 63 inches; Width, 24 inches; Depth, 16½ inches



Chaffee Gap.



D.C. Excitation



A.C. Excitation.

secondary helices (oscillation transformer), wave change switch, send-and receive switch, and hot wire ammeter. The motor starter for the motor generator and the generator field rheostat are also mounted on the front at the bottom. This particular transmitter operates on an a.c. supply although some have been operated on d.c. supply voltage. The cut of the diagram of connections will aid in making clear the operation.

The transformer whose secondary voltage is about 500 volts charges the condenser whose capacity is 0.16 m.f. The first cut shows two gaps which are used in series, each gap length is .002 inches. Hence the condenser will discharge at a potential of about 500 volts. Since the capacity of the condenser is very high in comparison to that used in the tuned primary transmitter, the discharge current will be very heavy, especially since the primary circuit consists of very heavy copper tubing. The primary helix consists of a single turn of heavy copper tubing closely coupled to the secondary helix. Due to the peculiar characteristic of this gap its resistance becomes very high as soon as the condenser discharge current has reached a maximum value and is completely reduced to zero in less than one half cycle. This single pulse of heavy current excites the secondary and connected antenna so that it oscillates freely at its own natural period as explained previously. The primary is not a tuned circuit hence the capacity of the condenser may be large enough to store the necessary energy in spite of the low voltage. The wave changing switch changes the number of turns in the secondary helix so that the antenna radiates at a lower wave length. Part of the primary condenser is cut out when the wave change switch is set for 300 meters so that the transmission is at reduced power. This is required by law. Note that when the antenna transfer switch is thrown to receiver the generator field is opened.

The transmitter illustrated in the first cut is of .5 K. W. capacity. The third cut shows this same transmitter mounted on a wall bench on shipboard, the motor generator being mounted on the floor. The transmitter panel is extremely compact being only 18 inches wide and 28 inches high on its front side. It is designed for small freighters, cutters, etc., and with the ordinary antenna on this type of craft gives a radiation current of from five to nine amperes. The next cut shows a 2 K. W. transmitter of the same type. The last cut shows a sectional view of the Chaffee gap together with a retouched Braun tube oscillogram of the currents in primary and secondary. Transmitters built to operate on the same principle are also manufactured by the Kilburn Clark Co., and Haller Cunningham Co., and are in common use in ship and land stations. A more complete description is given of the Cutting and Washington Transmitter in the Proc. I. R. E., December, 1918, p. 295.

CHAPTER IV

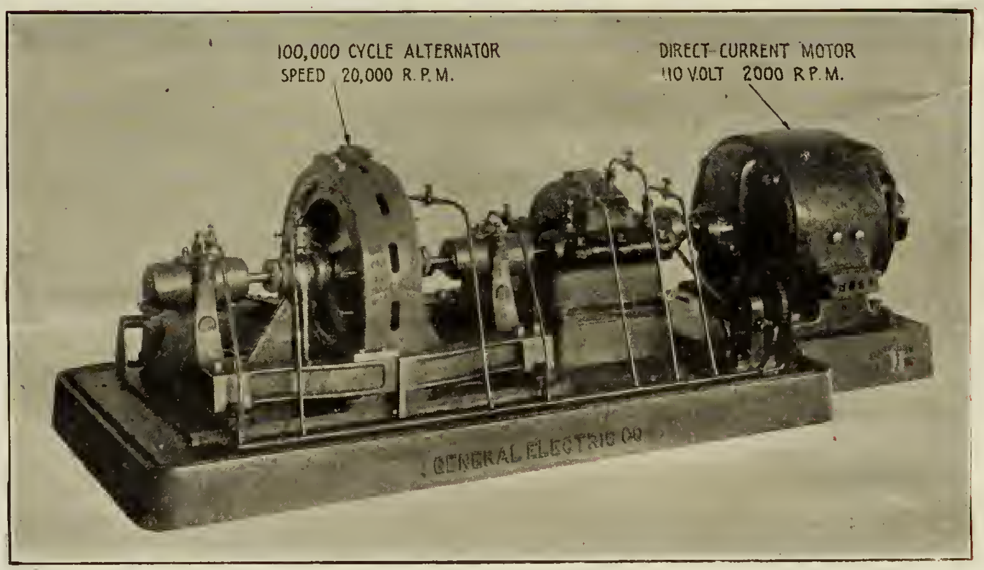
UNDAMPED WAVE TRANSMITTERS

I. Distinction Between Damped and Undamped Waves.

If an antenna, or other radiator were charged the resulting discharge moves back and forth from one plate of the condenser to the other until it is finally dissipated in the resistance of the circuit, emitting a damped wave. Obviously if the total resistance were zero the oscillation would not decrease and the wave would be undamped, its logarithmic decrement would be zero. While it is impossible to do this it is possible to produce the undamped wave by continually exciting the antenna while it is oscillating. If an alternator or other type of generator of undamped alternating e.m.f. is connected in series with an antenna as shown in Fig.29 undamped waves will be set up, for the antenna is charged and discharged by the simple application of an a.c. voltage to a condenser, the condenser current leading the voltage wave by 90°. The inductance L is adjusted (with the key K down) until the series circuit of capacity inductance and resistance are in resonance with the frequency of the alternator G. This is a case of simple series resonance, and undamped oscillations are set up due to the continuous energy supply of the alternator. When the key is released the value of L is changed changing the wave length slightly and decreasing the intensity of oscillation; thus signals are sent. This is the principle of the undamped wave transmitter using an alternator.

II. High Frequency Alternators.

The type of alternator used must have a frequency which will give the desired wave length. For instance, if the wave length is to be 6000 meters the frequency of the alternator must be 50,000 cycles. Such alternators must be of special construction, and the Alexanderson high frequency type deserves a brief description. This machine is of the inductor type, but the method of construction is very different from the usual type of low frequency alternator. The armature winding of the latter machine would have too high a reactance at such frequencies to make it of any use as a radio generator. Fig. 30 shows several views of the Alexanderson alternator. A is a longitudinal sectional view through the shaft. The field winding consists of two coils F_1 and F_2 the wires of this winding pass around inside the field core C' concentric to the rotating disk D. The dotted line shows the path of the lines of force. The disk D is slotted radially and the projections thus formed cause a varying reluctance in the gap M N as the disk turns on its shaft. Hence the


100,000 CYCLE ALTERNATOR
SPEED 20,000 R.P.M.
DIRECT-CURRENT MOTOR
110 VOLT 2000 R.P.M.
GENERAL ELECTRIC CO

flux pulsates and the conductors of the windings S_1 and S_2 have high frequency voltage induced in them. This winding consists of conductors zigzagging back and forth in radial slots. A view of the winding looking parallel to the shaft in the direction of the arrow H would appear as in B of the Fig. C is a plan view from above the machine showing the projections on the rotor. The slots in the rotor and stator are filled with brass wedges so as to reduce windage to a minimum. The rotors have as many as 300 teeth or projections and rotate at high speeds, sometimes at 20,000 R. P. M. It may be designed for frequencies of 25,000 to 200,000 cycles. It may be noted that the frequency is obtained from the simple relation $f = \frac{R\,P\,M}{60} \times$ Number of Teeth on Rotor. The latest installation of a machine of this type is in the U. S. Naval Radio Station at New Brunswick, N. J. This installation is described in Chapter VIII. A cut of a generator of this type is found opposite this page. The alternator is connected through a gear and pinion to a direct current motor. The Goldschmidt alternator generates high frequency voltages on a different but ingenious principle. It is used in German high power stations. It is described in Zenneck, p. 216, or Lauer and Brown, p. 125.

By using a radio frequency changer a frequency of 50,000 cycles may be obtained from a 25,000 cycle source. Since future development is opening up for the use of such a system the simple radio frequency changer for doubling the frequency will be described briefly. Fig. 31 shows the connections of such a system. G is the 25,000 cycle generator. Normally the cores of the transformers T and T_1 are saturated by the d.c. winding, the heavy arrows showing the direction of flux in each core. When current flows from the generator through P and P_1 the magnetomotive forces aid the d.c. magnetomotive force of one core while opposing that of the other. The flux in the first core T_1 is not increased because the iron is already saturated, but the opposing m.m.f's. in the core of T weakens the flux, and hence a complete wave of e.m.f. will be generated in S during the time of a half wave of the e.m.f. of G. On the next half wave another full wave will be generated in S_1. Hence the charging current of the antenna will be of double the frequency of the generator. By using another set of such transformers the frequency may be again doubled. For a full discussion of these circuits see the "Wireless Age", November and December, 1918, and January, 1919.

III. Arc Generators.

A direct current arc shunted by an inductance and capacity generates undamped oscillations and, as it is used as a generator in nearly all the U. S. Navy high power stations it will be dwelt on at some length in order to make its operation

clearly understood. The "arc generator" as it is called, is connected as shown in Fig.32

The arc is maintained by a d. c. generator at about 500 volts. The heavy choke coil and resistance in the line have the effect of maintaining a constant supply current in the line. C and L form a sort of series resonant circuit, the frequency of the charging and discharging current being dependent somewhat upon the value of L and C. The characteristic of the arc and the circuit is such that undamped oscillations will be set up in the circuit L C. Fig. 33A shows what is known as the static characteristic of a d. c. arc. As the current in the arc increases the voltage across the arc decreases, and according to Steinmetz obeying the relation

$$E = e_1 + \frac{K\,(1 + 1_1)}{I}$$

where e_1 is the voltage required to produce incandescence at the negative electrode and $\frac{K\,(1 + 1_1)}{I}$ is the voltage consumed in the arc stream. $K(1 + 1_1)$ is a constant depending on mechanical features of the arc. The curve has a negative slope, i.e. $\frac{dE}{dI}$ is negative, and it is said to have a negative resistance. It is easy to explain how oscillations are generated due to the arc characteristic. Imagine for the moment the current of the arc to decrease slightly. Following its characteristic the voltage E rises and charging current would begin to flow into the condenser. Since the line current is constant the charging of the condenser must take some of the arc current which would increase the voltage causing the condenser to take still more charging current, and a further increase in voltage due to decreased arc current until the latter becomes zero. The potential of the condenser then becomes sufficiently high due to resonance to reignite the arc and the condenser begins to discharge through the arc increasing the current and decreasing the voltage until the condenser is discharged, and the cycle is repeated.

As a matter of fact the characteristic only follows curve A, Fig. 33, when the current changes slowly so as to give the temperature of the electrodes and gases in the arc stream time to change. If the current varies at a high rate the change in temperature will lag and the characteristic will take the form of curve B. When the current decreases from I_2 to I_1 E follows part a of the curve and for an increase E decreases along b.

It is therefore best to describe the action by considering the variation of current through the arc during the process of charging and discharging of the condenser.

The constant current supply from the generator is represented by i_0 on the diagram of Fig. 34 and O^1 is the axis of zero charging current in the condenser and O is the axis of zero current in the arc. At the point a the condenser is fully charged and its voltage E_1 is a maximum at a^1. The discharge current increases to a maximum at b and the arc current is the discharge current of the condenser plus the constant supply current i_0 or the arc current is b b". At this point the voltage E_1 of the condenser has fallen to nearly zero and as the magnetic field has inertia the current will persist in the same direction until the condenser is charged oppositely. The current has died down to zero at c and the E_1 is now negative maximum at c^1. The condenser current now begins to increase in the opposite direction but it is now opposite to i_0 in the arc and hence the two currents will subtract and the resulting arc current is zero because the voltage is not sufficient to start an arc in the opposite direction. The condenser again discharges and charges to maximum positive voltage, but it will be noticed that during the latter half wave of condenser current the loop was flat. Hence the oscillations in the condenser circuit and arc are not sine waves. From the above explanation it will be seen that the curve I represents arc current in reference to axis O and condenser current in reference to axis O^1.

Since the maximum condenser current in one direction can only be i_0 it will take a longer time for the condenser to discharge and recharge hence c d will be longer than a c. When the arc is burning its voltage is low hence the dotted wave E represents the voltage of the arc when current flows. When the arc current is zero the arc voltage follows the condenser voltage E_1. The diagram at the right in Fig. 34 is what is known as the "cyclic curve" of arc voltage and current. Starting at b the current decreases to e just as it does in the arc current wave at the left. Then the voltage increases in a negative direction from e" to e^1 just as it does in the arc voltage wave. The arc voltage rises from e^1 to f^1 and then drops back to g" when the arc current begins to rise. Due to the dynamic characteristic of the arc, previously explained, the cyclic curve will take the form shown in Fig. 35 while the actual shape of the arc and condenser oscillations will be as shown in this Fig.

The above are known as "type II oscillations, and are further discussed in Zenneck p. 234 - 236 and p. 239 - 245. When studying the material of this reference it must be remembered that the condenser must discharge and recharge in the opposite direction to account for the reversal of potential of the condenser and the arc. This is not stated, making the physical phenomena difficult to understand. This type of oscillations is that required for the arc transmitter, as the energy in the oscillations is very great even though the latter are not sinusoidal in form.

The connections of the Poulsen arc transmitter are shown in Fig. 36 The arc has a transverse magnetic field produced by the d.c. supply current to the arc. The effect of this is to give the arc a very steep characteristic and extinguishes it at the end of each half cycle. The variation of E_a and I is shown in the curve of Fig. 36 . The variation of arc current in this system is very great, and heavy condenser charging currents are obtained, hence it is practical for high power stations. When the key K is depressed all of the antenna loading inductance is in circuit and the emitted wave is of a certain value. When the key is released some of the inductance is short circuited decreasing the wave length about two per cent. The receiver is so adjusted that it responds to one wave length better than another. The generator supplying the arc current is usually a 500 volt direct current machine. Some operate at higher voltages. During operation the length of the arc must be continually adjusted so as to keep up maximum radiation as indicated by the radiation meter. When the radiation is maximum type II oscillations are being generated. The arc is shunted directly by the inductance and capacity of the loading coil and antenna and earth, as the ratio of inductance to capacity of the antenna and coil is about correct for the generation of oscillations of the proper type. If the shunt capacity is very large a comparatively long time is required to discharge and charge the condenser by the constant current supply resulting in oscillations of the type shown in Fig. 37 . These oscillations are similar to what are obtained in the primary circuit of the impact transmitter using the Chaffee gap or the several types of "arc gaps".

IV. Undamped Waves With Rotary Dischargers.

In its trans Pacific stations the Marconi Company makes use of a high speed multi gap synchronous rotary discharger in a circuit very similar to the 2 K. W. quenched gap ship transmitter previously described. The wave length being 17,000 meters the oscillation frequency is comparatively low so that one oscillation in the antenna has not had time to decay appreciably before the discharger begins the next succeeding oscillation. This results in practically an undamped wave. In the older trans Atlantic stations of this Company several condensers were successively discharged by a set of dischargers revolving on the same shaft but with electrodes so spaced that condensers discharged in rapid succession into the same discharge circuit which was inductively coupled to the antenna. In this case as in the former the antenna oscillations merge into one another forming an almost undamped wave. The antenna oscillation looks as in Fig. 38.

V. Other Methods of Producing Undamped Waves.

Among transmitters using other methods of producing undamped waves may be mentioned the vacuum tube transmitter and the Chaffee gap. The principle of the former will be explained

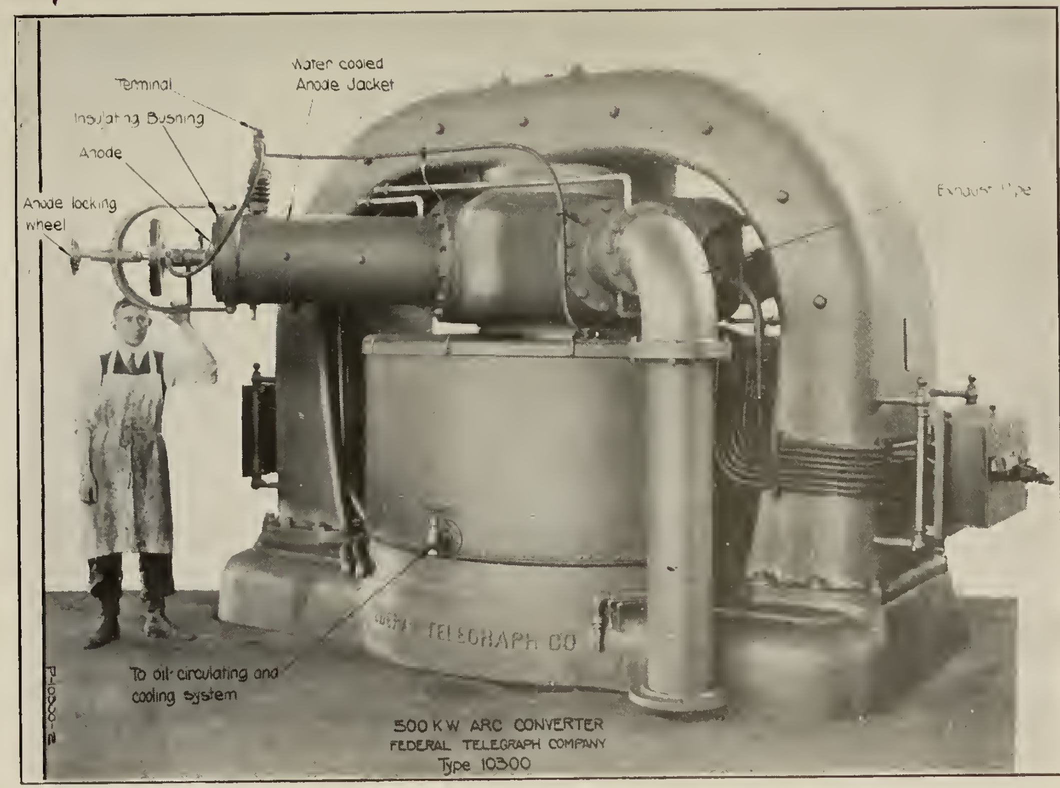


FIGURE 44—500-Kilowatt Arc Converter (Anode Side)

Arc Chamber

FIGURE 13—Arc Set, Arlington

in the discussion of vacuum tubes in the next Chapter. Recalling the description of the Chaffee gap in connection with the Cutting and Washington impact transmitter in Chapter III, the tone circuit shunting the gap (See Fig. 28) can be so adjusted that the gap will discharge at radio frequencies allowing only two or three antenna oscillations between gap discharges. The resulting emitted wave is practically undamped. For such operation direct current excitation is used. For a discussion of this feature see Proc. I. R. E., December, 1918, p. 300.

VI. Poulson Federal System of the U. S. Navy.

All of the U. S. Navy High Power Stations with the exception of the New Brunswick Station use the Poulson arc. The circuit is practically that of Fig. 36 . This system is known as the Poulsen Federal System. The arc producing apparatus are known as "arc converters". A large and small size are shown in accompanying cuts. They range in capacity from 75 K. W. at the Darien Panama station to 350 K. W. at Annapolis, Md. Note the immense size of the iron magnetic circuit of the large size converter, and the horizontal position of the electrodes. These arcs are regulated by hand feed during operation.

VII. Advantages and Disadvantages of Undamped Waves.

The mathematical derivation of the radiated fields indicates that the shorter the wave length the stronger the field, but when the absorption factor is considered this is not the case. In fact experience shows that the best wave lengths for trans-oceanic telegraphy are from 9,000 to 17,000 meters. Undamped waves are desirable because the difference between day and night transmission is quite small, whereas with damped waves the variation is 200 to 300 per cent. So it is desirable to use undamped waves of great length, and the Poulson arcs and high frequency alternators meet this requirement admirably. The wave emitted by an oscillatory circuit having L, C, and R will have a logarithmic decrement depending on the value of R above, $\delta = \frac{R}{2 f L}$. If a wave meter is coupled to the above circuit and the capacity of its condenser varied resonance or tuning curves are obtained as shown in Fig. 39 . For low values of R the resonance is very sharp as shown, and for high values it is not very marked. Hence the lower the decrement of the emitted wave the greater the sharpness of tuning. Since the decrement of the undamped wave is zero it follows that the resonance is very marked and the tuning extremely sharp. Undamped waves, then have an advantage over damped waves in tuning. Lower voltages can be used to excite the antenna with undamped waves than with damped waves because the antenna is steadily excited and with constant intensity whereas in the case of damped excitation the antenna is excited at short intervals and with decaying currents. This makes for greater efficiency with undamped waves.

For low power transmitters undamped waves are not practicable on account of the great space required for loading inductances. On shipboard the antenna is small and for transmission at 6000 meters the necessary loading coils would occupy too much space. Neither the arc nor the alternator is feasible for transmission below 6000 meters, the difficulty in the case of the arc being due to bubbling, and in the alternator due to complicated construction, space and weight. Low power short undamped wave vacuum tube transmitters have been developed in sets for military use and have proven very successful.

CHAPTER V

RADIO RECEIVERS - VACUUM TUBES

I. The Simple Inductively Coupled Receiving Circuit.

Before taking up the operation of a receiving circuit the student should be familiar with the characteristic of the crystal detector. If a fine wire touches lightly upon the surface of a piece of galena it will be found that the resistance to the flow of current in one direction is greater than for the opposite direction. A firm blunt metal contact on silicon, or a sharp steel point contact on carborundum produces the same result. The variation of current flowing through such a contact with the applied voltage to the crystal contact is shown in Fig. 40. Such a device, then, is really a rectifier. Its rectifying ability varies with a constant e.m.f. applied to the contact, and there is a critical voltage where the rectification or "sensitiveness" is a maximum. Very often a small low voltage battery and potentiometer is used to maintain the best voltage on the crystal for rectification purposes. At present the use of crystal rectifiers is largely limited to measuring instruments such as wave meters, and for rectifying feeble radio frequency currents so that their value may be determined by means of a D'Arsonval galvanometer. However, crystals are still used as detectors in some receivers on shipboard. The carborundum steel rectifier is the most rugged and has the most steady adjustment, hence has been the standard in the past for use on shipboard. The crystal detector will be explained presently in the discussion of the radio receiver. For characteristics of other crystals see Pierce, Chapter 17.

The most direct method of studying the phenomena of receiving is to examine the simple inductively coupled receiving circuit with crystal detector, and coupled inductively to the antenna. Such a circuit is shown in Fig. 41. The electromagnetic waves pass across the antenna and the interlinking of the magnetic lines of force with the antenna conductors generates potentials in the latter, and of the same frequency as that of the impinging waves. The resulting currents induced flow back and forth from antenna to earth and in so doing induce potentials in the secondary S of the receiving transformer or "loose coupler" P S. Currents will flow back and forth between S and the variable condenser C and alternating voltages will be

impressed upon the crystal detector D. If the incoming waves are damped the potentials at C will be of the same nature as the incoming waves, but with greater damping due to the resistance of the receiving circuit. For a dot signal the potentials at C may vary as shown in Fig. 42A. These potentials are impressed on the crystal detector, but owing to the peculiar property the crystal contact has of being more conductive in one direction than in the other currents will flow in only one direction as shown in part B. A portion of these pulsating currents flow through the telephone receivers T, Fig. 41, and owing to the high inductance of the windings the pulsating currents merge into one pulsation for each wave train as shown in part C, Fig. 42. Thus it is seen that the diaphram makes one vibration for each wave train, and if the discharge or wave train frequency is 1000 the frequency of vibration of the receiver diaphram will be 1000 or slightly lower than high C on the piano. It is obvious that a mechanical diaphram could not vibrate at radio frequencies, but if it could the human ear could not hear the sound. The stopping condenser is used to shunt the telephones and serves to reinforce the receiver currents by either causing charges to pile up and move around through the receiver, or by a kind of audio frequency resonance between telephone reactance and stopping condenser capacity.

The next consideration is the process of tuning the receiving set. Referring again to Fig. 41, the inductance of P is varied until the natural frequency of oscillation of the antenna, coils L and S, and earth is the same as that of the generated potentials. This increases the induced currents in the secondary. Next the capacity of condenser C is varied until the secondary oscillating circuit is in resonance with the induced potentials and the oscillating current between L and C will be a maximum. The coupling between P and S is continually changed during the above adjustments so as to find the optinnum value of coupling. Changing the coupling after resonance is obtained reduces the current greatly due to the destroying of resonance caused by a change in the mutual inductance of the circuits. The resonant current causes maximum voltage drop across the terminals of condenser C and therefore maximum currents in the telephones. The question may be asked, why not put an indicating or recording instrument in place of the telephones? This has been attempted but with little success because of the fact that the currents in receiving circuits are usually measured in micro amperes, and no recording instrument or mechanical relay has been perfected which will function properly with such currents. There are many modifications of the connection scheme of Fig. 41 which are much used but cannot be dwelt on here. For instance, the condenser C may be connected to coil P, using another sliding contact to vary the number of turns across C. This scheme is called "direct" coupling and the coil P would be replaced by a "double slide tuner" or a "three slide tuner". Fig.   shows some modifications of the receiving circuit described. In the first the "potentiometer" is used to impress a constant potential on the crystal so as to give it maximum

sensitiveness. The second circuit is very simple and easily adjusted but the tuning is not well defined and strays are very loud in the telephones. The third circuit is known as the "aperiodic" or untuned secondary receiver. It is used in the new Unicontrol Receiver described in Chapter VIII. In all radio receiving circuits very sensitive telephone receivers must be used. The sensitiveness of a receiver is indicated by its resistance. Resistances of such receivers range from 2000 to 20,000 ohms, the latter being extremely sensitive. Dr. Kennelley found that a current of about .05 microampere will produce an audible signal in a sensitive receiver. For a discussion of telephone receiver characteristics see Mills, p. 26 - 35.

For the reception of undamped waves a device for interrupting the circuit 300 to 500 times per second must be connected in series with the telephone receivers. This device is called a "chopper" or "tikker". If it were not for this audic frequency interruption of the circuit there would be just one pulse of current in the telephones for each dash and dot causing faint clicks instead of buzzing tones.

II. The Two Element Vacuum Tube.

A preliminary consideration of the two element vacuum tube brings out important characteristics of the various types of tubes. A highly evacuated tube containing a filament and plate electrode is shown in Fig. 44A. When the filament is heated to incandescence an emission of electrons will take place due to the high molecular agitation of the hot filament and the high surrounding vacuum. A space charge soon accumulates in the evacuated tube so that additional electrons emitted are driven back into the filament because of repulsion of these latter by the free electrons of the space charge. If now the plate electrode is connected to a positive source of e.m.f. and the filament to the negative (a 50 volt battery), Fig. 44B. the positively charged plate will attract electrons, and as fast as they are attracted new electrons are emitted by the filament up to a certain limit described later. This flow of electrons to the plate is nothing more than a flow of current from plate to filament across the evacuated space. If the plate potential is increased the current will increase in the same proportion until a point is reached where the plate voltage attracts electrons as fast as they can be emitted by the filament at that temperature. An increase of plate voltage above this point will result in little increase in current. This is the saturation point. If the filament temperature be increased higher values of current will be obtained before saturation is reached. This is illustrated by the curves of Fig. 45A. If the plate voltage be maintained constant at some value E^1_B and the filament temperature increased the plate current will at first increase because the plate can attract electrons faster than they are being emitted. When the filament emits electrons faster than they can be removed by the positive plate, the excess electrons form the space charge, and this begins to exert a repelling force on

emitted electrons. When the space charge reaches a certain value due to increased temperature all additional electrons are repelled and reenter the filament. This is shown in Fig. 45 B. If the plate voltage is increased the saturation point will be higher, i.e. a higher filament temperature will be reached and also a higher plate current before the latter becomes constant. The mathematical relations between plate current and voltage and dimensions of the tube have been worked out by various investigators. Some of these will be given later.

III. The Three Electrode Vacuum Tube (Audion).

From the above it is seen that the current depends upon the space charge such that if the space charge is increased the current is decreased due to the repulsion of the space charge upon emitted electrons driving them back into the filament. Anything that could be done to reduce this space charge would increase the current for a given plate voltage. De Forest accomplished this by putting a wire grid between the plate and filament and charging the grid positively. The positive charge on the grid absorbs some electrons, reducing the space charge and increasing the current from plate to filament. Suppose the three element vacuum tube to be connected as shown in Fig. 46 . C is a battery to provide a variable potential on the grid G, which potential may be designated as E_C. The plate current will be called I_B and the plate voltage E_B. Fig. 46 also shows what is known as the characteristic curve for this tube. At a certain negative value M of E_C the plate current is reduced to zero. The reason for this is that the negative grid repels all emitted electrons from the filament. For zero grid voltage there is a certain value of I_B for each assumed value of E_B as shown. As E_C is increased positively saturation points are again reached where further increase in E_C does not increase I_B. At this point the negative space charge has been neutralized and the positive grid is aiding the positive plate in absorbing the electrons as fast as they can be emitted at that temperature.

IV. The Operation of the Vacuum Tube as a Detector of Damped Oscillations.

The action of the three element tube as a detector may be best understood by first considering its action without the so called "grid condenser". Fig. 47 shows the usual receiving circuit using the vacuum "valve" as a detector. The oscillatory circuits are tuned in the usual manner, and the plate voltage and filament current are adjusted for maximum strength of signals. The potentials impressed upon the grid G by the oscillation of currents in the secondary circuit cause the plate current to flow as shown in Fig. 48 . The cell at C, Fig. 47, keeps the grid potential normally at M, Fig. 48, (E_C). The incoming oscillations cause the grid potential to vary about this value as shown. The accompanying characteristic curve shows that if E_C were increased above M a certain amount the plate

current will be increased greatly but if it is decreased below M the same amount the amount of change is not so great. Hence the variation of plate current will be as shown and the pulses in the telephone as shown. The grid battery C may be omitted, and a tube used having a characteristic curve as shown in Fig. 49 . For this case the grid potential oscillates about zero and the resulting plate current and telephone pulses are as shown in the Fig. The variation of E_c is about M, which is the point of zero grid voltage, and is near the saturation point of the tube, and the tube will give audible sound in the phones.

For the best operation the tube is connected as shown in Fig. 50 . A small variable condenser of about .0005 m.f. capacity is connected in series with the grid. This insulates the grid so that electrons accumulate upon it increasing the space charge and reducing the plate current. When the antenna is set in oscillation by incoming waves oscillating potentials are impressed upon the grid condenser and induced upon the grid. During the intervals when these potentials are positive more free electrons are attracted to the grid increasing its negative charge, but this excess negative charge cannot be driven off easily by reversal of the oscillating potential. Hence an additional persistent negative charge accumulates on the grid during the oscillation of the receiving circuit, and reduces the plate current. When this excess negative charge leaks off the grid the plate current increases to its former value. A resistance of about 2 megohms is usually connected from grid to filament to facilitate the leaking off of the charge on the former. This resistance is known as a "grid leak". Fig. 51 shows the variation of grid voltage, plate current and pulses when the grid condenser is used. This type of detector may be called a potential detector as it depends for its operation only upon the potentials induced on the grid. The energy consumed in producing the audible signal is furnished by the "B" battery, and may be many times the energy consumed in the antenna during the oscillation. The crystal detector is what is known as a current detector, and all the energy used in producing the audible signal is furnished by the antenna oscillation. Obviously the vacuum tube or audion detector is much more efficient than the crystal form and has practically replaced this latter for all kinds of radio receiving.

V. Vacuum Tubes as Amplifiers.

The vacuum tube may be used as an amplifier from the fact that a small change in grid voltage will cause a large change in plate current. It requires only an extremely small energy to effect a change in grid potential, and the resulting change in plate current is considerable, and hence the energy of the output circuit (plate circuit) is changed considerably in proportion. Suppose a tube to have the characteristics of Fig. 52. If the grid potential is maintained normally at - M a variation of E_c of the same amount on either side of M produces the same change in I_B the tube is said to be a true amplifier.

In Fig. 53 is shown an application of the amplifier tube. The transformer T will furnish power to some circuit with an e.m.f. wave exactly similar to that of the generator. This is the principle of amplification of telephone currents by means of the vacuum tube repeaters used in long distance telephony. The use of an amplifier to increase the loudness of signals is important in the art of receiving. Fig. 54 shows a vacuum tube detector, and "single stage" amplifier. D represents the detector and A the amplifier.. T is an intensifying transformer of high impedance, and the second tube is known as an audio frequency amplifier. It may be noted that the same high voltage battery supplies the plate circuits of both tubes. The same filament battery may be used for both filaments but two are shown for the sake of simplicity in the diagram. Still another tube may be used to amplify the plate currents of the amplifying tube in Fig. 54 . Such an arrangement would be known as a "two stage" amplifier detector. It is not practicable to build more than two stages into an audio frequency amplifier on account of excessive noises. A single stage amplifier gives an energy amplification of 400 times and an audibility amplification of 20 times, while a two stage amplifier gives 160,000 times and 400 times respectively.

VI. The Vacuum Tube Generator.

The three element vacuum tube has the peculiar property of generating oscillating currents, if properly connected, just as the d.c. arc. Suppose a vacuum tube to be connected as shown in Fig. 55 . If current is flowing in the plate circuit any momentary increase in plate current causes a change in field due to the current change in "tickler" coil T and sets up an induced e.m.f. in coil L. This induced e.m.f. may be of such a character as to increase the potential on the grid positively. The result of this is a still further increase in plate current. This action is cumulative until the saturation point is reached when the plate current ceases to increase. The excess positive charge on the grid leaks off and the momentary decrease in plate current generates a negative potential on the grid which still further decreases the plate current and this process is repeated until the plate current is reduced to zero, after which the negative charge decreases and the plate current again starts to rise while the grid potential again becomes positive in small increments. The circuit L C oscillates at its own natural frequency and the pulsation of plate current occurs at the same frequency, or $\frac{1}{2\pi\sqrt{LC}}$. Thus the tube generates oscillatory currents in the circuit L C, the energy being furnished by the plate battery. Investigation shows that the oscillations generated are of nearly pure sine wave form and undamped. It must be remembered in the above explanation of the manner in which oscillatory currents are generated that the increase or decrease of plate current with grid voltage does not take place along the static characteristic curve of the tube. An increase of plate current is accompanied by a decrease in plate voltage

in the tube. It has been shown that the variation of plate voltage in the tube generator is in opposite phase to the variation of plate current and hence the grid voltage. Fig. 56 shows a set of characteristic curves taken for a transmitting tube at various voltages. As the grid voltage increases the plate current increases along the dotted line A B due to the fact stated above. The curve A is called the "dynamic" characteristic of the tube. The slope of this curve depends upon the coupling of the grid and plate circuits.

This property of a vacuum tube is made use of in receiving undamped wave signals. The circuit for such reception is shown in Fig. 57 . The Receiving circuit is generating oscillating currents in the circuit L_2 C whose frequency depends upon the values of C L_2 and initial inductance and capacity of the coupled antenna circuit. When undamped waves from a distant station generate potentials in L_2 the resulting current in L_2 has a frequency equal to the difference between that of the incoming waves and that of the generated oscillations in the tube circuit. This difference in frequency is called the "beat" frequency, and the pulsating currents in the telephone will have this same frequency which, of course, must be within the limits of audition. The beat frequency can be varied by variation of either C_1 L_2, L_1 or L, and the pitch of the received signal will vary accordingly. The ability to change the pitch is of great advantage when receiving through interference or strays.

VII. Beat and Amplifying Receivers.

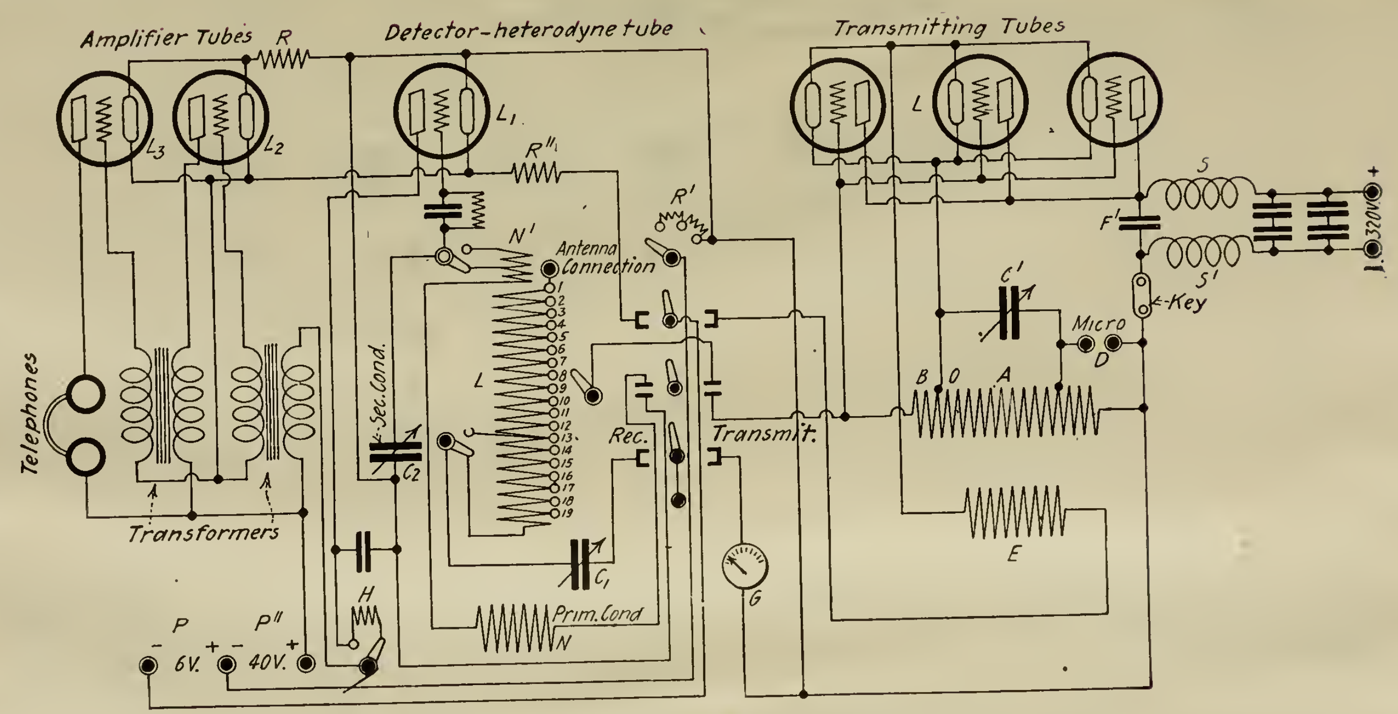
The operation of a beat or heterodyne receiver depends upon the coupling between the grid and plate circuits. The coupling may be capacitative as well as inductive. A very successful form is shown in Fig. 58. The condenser C_2 couples the grid and plate circuits. In its simplest form it is a 34 plate variable condenser (.001 m.f.) immersed in best grade castor oil. The capacities of the various condensers in micro farads are as shown in the Fig. For long wave reception, L_1 and L_2 should each have a maximum of 75 or 100 millihevries. This is one of Mr. Armstrong's circuits and he has shown (Proc. I. R. E. April, 1917) that by the aid of its regenerative action may give a total amplification of as much as 5000 times in beat reception. Beat receivers will also receive damped waves but the note of the signal is not the true note of the spark gap as in plain audion or crystal detector reception. When the circuit is correctly adjusted regenerative action is set up and the spark is heard as a hiss in the telephones. For regenerative beat reception of short damped waves, 200 to 600 meters, especially designed receiving circuits are in use. One well known type of beat receiver known as the "ultraudion" is shown in Fig. 59 . A one or two stage amplifier may also be used in conjunction with a beat receiver. One form is shown in Fig. 60. For descriptive discussions see Bucher, "Vacuum Tubes in Wireless Telegraphy", Bulletin No. 74, p 200-221; or Lauer and Brown, "Radio Engineering Principles."

VIII. Vacuum Tube Transmitters.

If the vacuum tube circuit arranged to generate oscillatory currents is coupled to an antenna and the antenna circuit properly tuned to resonance electric waves will be set up and the apparatus is a vacuum tube transmitter. By opening and closing the plate circuit with a key dots and dashes may be sent. The vacuum tube used for this purpose must be of a type which has a comparatively large plate current. This is obtained by using high plate voltages which range from 125 to 1500 volts, and probably higher voltages will soon be used. The Western Electric tubes make use of a "thoriated" filament. The thorium increases the flow of electrons at a comparatively low filament temperature so that the filaments burn at a dark red heat. A very comprehensive description of the small power vacuum tube transmitting sets developed by the Signal Corps will be found in the Wireless Age, October, 1919. Several tubes may be connected in parallel and to the same filament and plate batteries, thus increasing the power output. A diagram plate of one of the types used, the E 10 B 1 S set, is shown next to this page. There are great possibilities of using vacuum tube transmitters for low and high power telegraphy. At present it does not seem feasible with the tubes having a life of 1000 to 2000 hours to invest in costly transmitting tubes, with the heavy expenses for renewals. It is estimated that to operate the 100 K. W. Station at Arlington with vacuum tubes would require $10,000 per month for upkeep. The needed future development then, is in tubes having long life.

IX. Output Coefficients of Vacuum Tubes.

Certain constants of vacuum tubes are simple relations, and by their use tubes may now be designed for any particular purpose. Relative amplifying power output as a generator and detecting ability can be determined from the constants, hence the latter are given the name "output coefficients". When a three element vacuum tube is connected in a generating or receiving circuit there is a high voltage from plate to filament. The potential of the grid is almost that of the filament and the plate is positive to both. When the filament is heated the so called "thermionic emission" of electrons takes place and some move toward the grid. Some of these remain on the wires of the grid while others pass through the meshes, and on entering the region of strong electric field due the plate voltage are attracted toward the plate. Recalling the notation E_B is the voltage from plate to filament, I_B is the current from plate to filament (plate positive), E_C is the external voltage impressed on the grid. Even though the grid and filament be connected through a low resistance there is a difference between the potential of the grid and that of the filament due to the fact that the plate voltage causes a stray field through the meshes of the grid. Calling the potential thus produced at the grid E_s,



Circuit diagram of Radio Set Type E-10 bis

$$E_s = q\,E_B$$

where q is a constant. If the mesh is very fine the field passing through is zero and E_s and hence q is zero. If no grid were present $q = 1$ or $E_s = E_B$. q must then be less than one. Electrons emitted into the space between filament and grid will be attracted to the grid by the voltage E_s. As stated above some of the electrons reaching the grid remain upon it while the remainder pass through the meshes and travel onward toward the plate. Suppose that a voltage E_c were impressed upon the grid from the external circuit, and its value was equal and opposite to E_s. Then the resultant pull upon the electrons emitted from the filament into the space between filament and grid would be zero, and assuming a space charge in the tube, these electrons would be returned to the filament. If $E_c + E_s$ were positive the electron flow toward the grid would be increased. Van der Bijl has determined experimentally that

$$
\begin{aligned}
I_B &= (E_s + E_c)^2 \alpha \\
&= \alpha(E_s + E_c + \varepsilon)^2 \\
&= \alpha(q\,E_B + E_c + \varepsilon)^2 \qquad (9)
\end{aligned}
$$

where α is a constant depending upon the construction of the tube, and ε is a small constant allowing for small difference in potential between external connections between filament and grid. The rate of change of I_B with E_B is the partial derivative

of the above expression or

$$\frac{\partial I_B}{\partial E_B} = 2\alpha q(q E_B + E_c + \varepsilon) = A$$

similarly $$\frac{\partial I_B}{\partial E_c} = 2\alpha(q\,E_B + E_c + \varepsilon) = B$$

then $$\frac{\dfrac{\partial I_B}{\partial E_B}}{\dfrac{\partial I_B}{\partial E_c}} = q = \frac{A}{B} \qquad \frac{\partial E_B}{\partial E_c} = \frac{1}{q} = \mu$$

The rate of change of the plate voltage with respect to grid voltage $\mu = \dfrac{\partial E_B}{\partial E_c}$ is called the "amplification constant" of

the tube. The internal impedance of the tube would be the plate voltage divided by plate current, or if the ratio is variable

it would be the rate of change of plate voltage with respect to plate current.

That is, $$R_o = \frac{\partial E_B}{\partial I_B}$$

Since this is the reciprocal for equation fôr A above

$$R_o = \frac{1}{A} = \frac{1}{2\alpha q(q E_B + E_C + \varepsilon)}$$

$$= \frac{(q E_B + E_C + \varepsilon)}{2\alpha q(q E_B + E_C + \varepsilon)^2}$$

The slope of the characteristic curve of the tube, as shown in Fig. 61 is S

where $$S = \frac{\partial I_B}{\partial E_C} = \frac{1}{B}$$ see equation for B above.

Combining the values of μ and R_o above in the equation for B

$$S = \frac{1}{B} = \frac{\mu}{R_o} = \frac{1}{2\alpha(q E_B + E_C + \varepsilon)} \qquad (10)$$

This factor is known as the mutual conductance of the tube, and its quality is determined by the value of this constant. These three constants are worked out and discussed by Van der Bijl and Ballantine in the Proc. I. R. E., April, 1919. The above derivations follow their conceptions but in a simpler manner. Langmuir gives the equation for plate current as

$$I_B = A(E_B + K E_C)^{\frac{3}{2}}$$

as compared with

$$I_B = \alpha(q E_B + E_C + \varepsilon)^2$$

as given by Van der Bijl and discussed above. Langmuir's equation was probably derived for the upper part of the characteristic curve, and probably holds more nearly true for the Pliotron tube. Van der Bijl's equation was probably developed for the oxide filament Western Electric tube. The above equations and constants assume that all molecules of gas have been occluded or removed from the tube. The anode or plate often heats to a dull red heat in a power transmitting tube, and such temperatures cause the plate to throw off occluded gases, hence all traces of gas must be removed by heat treatment during evacuation. If the vacuum has become low the increase of plate voltage above a certain value causes a cathode ray discharge from filament to plate. The tube will not function as a detector, oscillator, or amplifier under this condition.

The value of a tube as a detector can be determined by what is known as the detection constant. Consider first a vacuum tube connected to a receiving circuit without a grid condenser. Since I_B changes with E_c the variation of E_c due to superimposed oscillating potentials produces variations of the internal impedance. If the mean steady grid voltage of the tube is M in Fig. 61 the oscillating potentials produce variations of ΔE_c and hence of $\Delta_1 I_B$ and $\Delta_2 I_B$ and the mean variation of plate current is

$$\frac{\Delta_1 I_B - \Delta_2 I_B}{2}$$

and the ratio of this change to E_c is

$$\frac{\Delta_1 I_B - \Delta_2 I_B}{2\Delta E_c}$$

For limiting values the expression becomes

$$D = \frac{d^2 I_B}{d E_c^2}$$

which is known as the detecting constant. Since the mutual conductance was shown to be $\frac{\partial I_B}{\partial E_c}$ it is seen that D is the derivative or rate of change of the mutual conductance of the tube. When the tube has a condenser connected in series with the grid a negative charge accumulates on the grid during the train of oscillations, as was previously explained. This means that there is a unidirectional charging current to the grid, and the detecting power of the tube depends upon the rate of change of this current also. Ballantine supposes that for this case

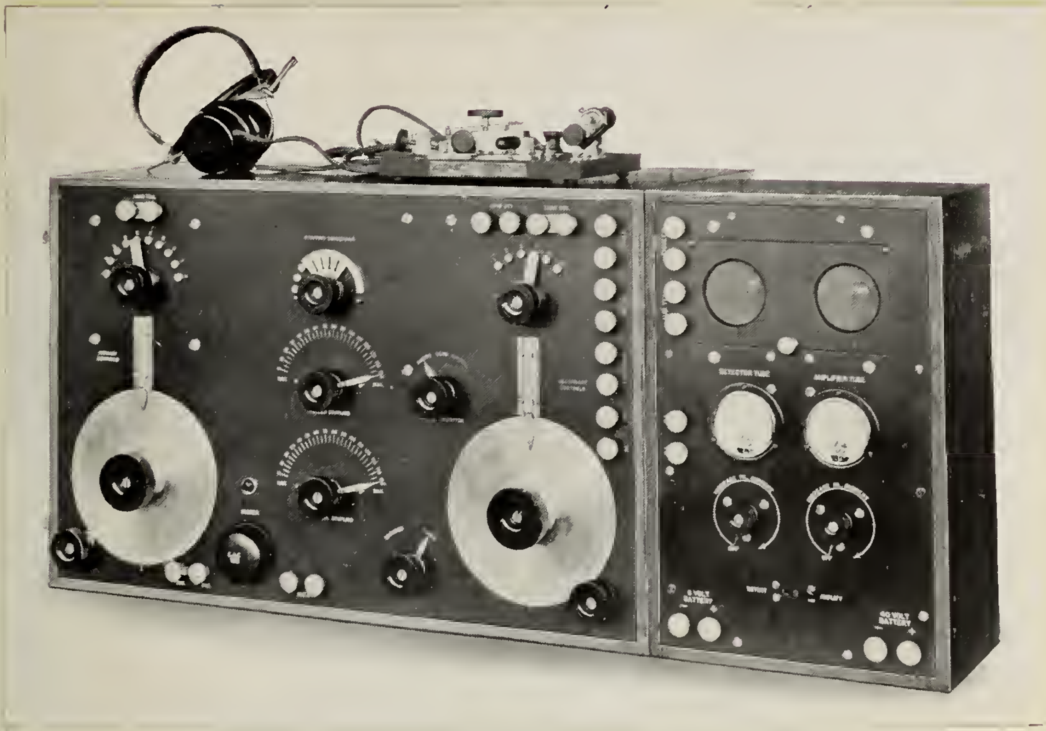
$$D = \frac{\partial I_B}{\partial E_c} \cdot \frac{d^2 I_c}{d^2 E_c^2}$$

(See The Operational Characteristic of Thermionic Amplifiers by Stuart Ballantine, Proc. I. R. E., April, 1919).

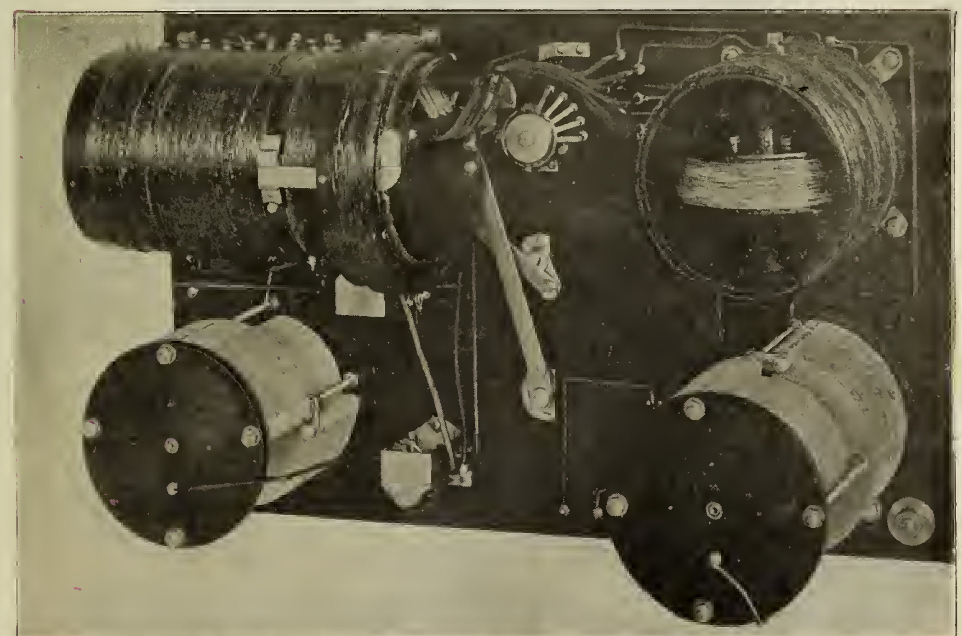
Various writers and investigators have proposed formulae for the various above tube constants which are unlike although most of them have many points of similarity to the above relations. The expression for detection power, however, is worked out quite differently, hence the above expression may or may not be correct. However, its deduction seems to be quite as logical as those for other relations.

X. Commercial Forms of Radio Receivers.

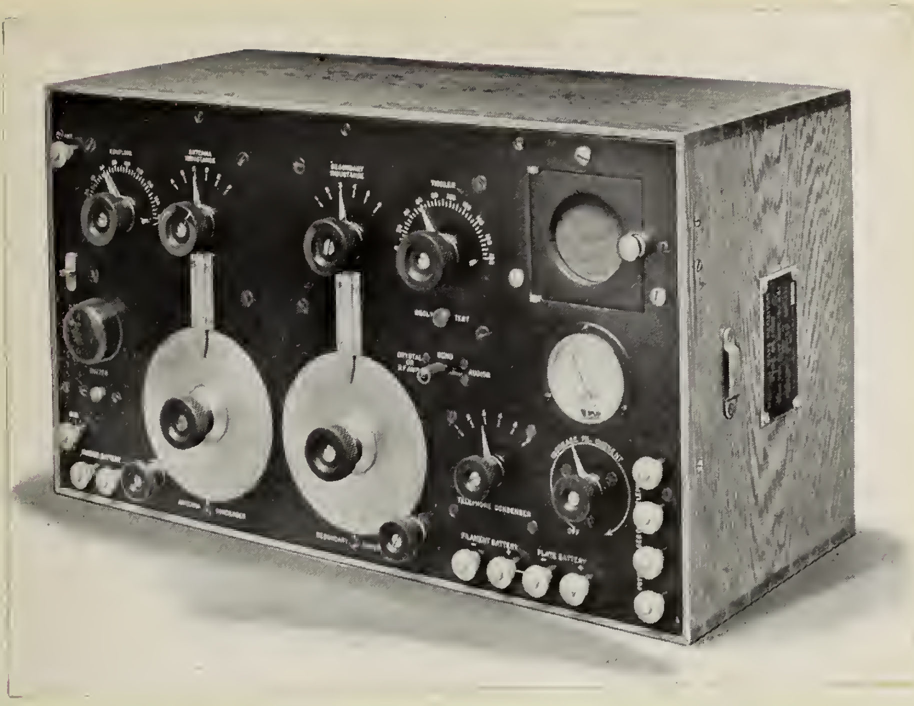
The type of radio receiver which is coming into most general use is one having the receiving transformer, condensers, vacuum tube detector with control apparatus, and sometimes vacuum tube amplifiers all contained in one cabinet the control devices being mounted on the front side which consists of black polished Formica bakelite. Receiving transformers for use in these cabinets are now made in many compact forms. It was formally thought that receiving transformer coils must be single layer solonoids so as to reduce the distributed capacity to a minimum. Such coils of course take up considerable space. It has gradually been realized that receiving transformer coils can be wound in compact forms such as "honey comb" coils, "involute" coils, etc., and that distributed capacity is not entirely detrimental especially for long wave reception. Very often the receiver circuit and detector tube with filament and plate battery control are included in one cabinet and the amplifier tube or tubes with controls included in a separate box. The plate batteries are usually in compact form, often consisting of a dozen three cell vest pocket flashlight cells connected in series; and are usually placed inside the cabinets. Several forms of cabinet receivers are shown on the plate next to this page.



Battleship Receiver with Two Stage Amplifier.



Rear View of the Battleship Type Receiver Clearly Exposing Its Engineering Features and High Standard of Design.



Battleship Receiver with Vacuum Tube Detector.

Short-wave Regenerative Receiver Type CR-2. Designed for long distance relay work on wavelengths between 170 and 580 meters. This receiver is characteristic of our advanced design and methods of construction and will fulfill the most exacting requirements.

"R.W.4" Size 12"x9"x6½"

CHAPTER VI

ELECTROMAGNETIC WAVES IN RADIO COMMUNICATION

I. Introductory.

The Engineer following his special line of activity accepts the laws of Physics and is principally interested in applying them for a particular result. It is the purpose of this chapter to consider the phenomena of electromagnetic waves in a very elementary way, and to apply some of the laws relating thereto to the derivation of the actual current received from a transmitting station. This will indicate to him what important factors affect the efficiency of radio transmission.

II. What Radiation Is.

The student of Electrical Engineering is accustomed to thinking of the magnetic field as closed lines of force about a conductor carrying current. As the current rises from zero the lines of force grow or expand outward from the center of the conductor, and when the current dies out the existing lines of force again collapse toward the center. This magnetic field about the conductor is known as the "induction field". The magnetic field which cuts the wires of the receiving antenna is a radiated field and the circumstances accompanying its production are quite different. The student should read carefully the elementary explanation of the creation and propagation of electromagnetic waves in the second paragraph of Chapter II. As previously stated this explanation is not complete and in order to clear up some points which will be made use of later a portion of Maxwell's theory of dielectrics will be reviewed.

III. Brief Descriptive Statement of Maxwell's Theory of Dielectrics.

Maxwell showed that an electric current was the phenomena resulting from the change of any exisitng electric strain or displacement, that is, while an electric strain is increasing or decreasing the effect produced is that of a current. If the electric strain existing in a dielectric is varying the result is called by Maxwell a "displacement current" (The charging current flowing into a condenser may be considered as flowing through the dielectric between the plates, and in this part of the circuit would be a displacement current). It is well known that

when there is a change in the magnetic flux existing inside a closed conductor an electromotive force is created in that conductor. Maxwell also showed that when magnetic flux through a dielectric or any other medium was changing an electric strain was created along a closed line drawn in this medium so as to enclose the flux. Take for example lines of force passing through a medium of dielectric such as paraffin. If a closed loop of wire was imbedded in the material and lying in such a position as to enclose some or all of the flux an electromotive force is created in the wire when the flux increased or decreased, and if the circuit is closed current flows. Now imagine the loop to be removed. The electric strain is still produced along that same line once occupied by the loop of wire, and along any other path in the dielectric enclosing lines of force. (It should be remembered that the line integral of the electric strain along a closed path gives the electromotive force).

Consider a long thin wire carrying current. At a point P at a distance r from the wire the field intensity due to the current in the wire can be shown to be equal to $\frac{2\ I}{r}$. The length of the line of force around the conductor in a circular path through this point is $2\pi r$ as in Fig. 62 . The summation of all the forces acting around the wire is then

This summation is the line integral of the magnetic force and is independent of the path around the wire. If the dielectric strain D is changing, which it must do when a displacement current flows, this latter, $I_D = \frac{d\ D}{d\ t}$, the rate of change of the electric strain. When the area around the displacement current is very small the line integral of the magnetic force divided by that area is called the "curl" of the magnetic force, or

$$4\pi \frac{d\ D}{d\ t} = \text{Curl of H.}$$

As stated above the e.m.f. is defined as the line integral of the electric force along the closed path, and the rate of variation of the magnetic flux through any area is a measure of the created strain, and e.m.f. generated, or the line integral of electric force around the path. For unit area

$$\frac{d\ \phi}{d\ t} = \text{curl E} \qquad E = \frac{4\ \pi\ D}{K}$$

It will be well to remind the student that the term "curl" really means more than is indicated by the above definition. In fact the curl is a mathematical expression and is not exactly definable in physical terms. If a charge is moved around a closed elemental path in an electric field an expression for the total work done can be obtained by projecting the path on the X, Y, and Z planes and expressing the work done in each of these planes. For the X Y plane the expression is

$$\left(\frac{d Z}{d Y} - \frac{d Y}{d Z}\right) d x d y$$

$d x d y$ is the area of the X Y projection of the elemental path, and if the above expression is divided by this area the resulting expression is what is known as the "X component" of the curl. The curl is a vector and its three components are

$$R_X = \frac{d Z}{d y} - \frac{d Y}{d z}$$

$$R_Y = \frac{d X}{d z} - \frac{d Z}{d x}$$

$$R_Z = \frac{d Y}{d x} - \frac{d X}{d Y}$$

which means that the curl is really a vector. For a simple elementary treatment of these quantities the student is referred to "Elements of Physics" by Nichols and Franklin, Vol II, Chapter I.

Comparing the relations derived it may be rather generally concluded that the variation of strain in a dielectric creates a magnetic field, and the variation of existing magnetic field gives rise to electric strain, and that the amount of the one created depends upon the rate of variation of the other.

IV. Radiated Fields.

In Fig. 63 the arrow may represent a displacement current in a dielectric. As previously explained this displacement current is the changing electric strain in the dielectric due to charging or discharging of a condenser, the plates of which may be imagined to be at each end of the arrow and parallel to each other. The displacement current will set up a line of force having the direction shown similar to the field about a wire carrying current. It was pointed out above that when the magnetic field existing in a dielectric changes a closed line of electric strain is created around the magnetic line or lines of force. Therefore when the line of magnetic force created by the displacement current dies out a second condition of electric strain is created.

Fig. 64 is a perspective view showing the relations of created flux and strain by the change in an original strain along A B such as produced by a condenser discharge. When the strain A B dies away the closed line of flux C is created. After A B ceases the field cannot remain so decreases and its decrease creates new closed lines of strain D and E, and as many other loops as can be imagined to exist around flux line or lines C. (The shape of the created field of strain can be better understood if D or E were imagined to be rotated about A B. The created strain is then in the form of a closed ring with flux line C as its center). This latter created strain D E, cannot

remain after flux line C ceases, hence it then begins to decrease creating a new flux line F. When F dies away strain G H is created again in the same direction as the original strain A B. It should be noted that this is a complete cycle of change thus, strain, flux, strain, flux, strain. Compare with the alternations between displacement and motion of the particles in a complete cycle of a water wave. This cycle is repeated and the successively created flux lines become larger and larger until the energy of the disturbance is finally absorbed in the resistance of the dielectric medium (no dielectric is a perfect insulator). This explains in a rough way the nature of an electromagnetic wave. A word of caution is necessary. It must be remembered that the medium is homogenous and the created fluxes and strains are not in the shape of concentrated rings. For instance, the flux C created by decrease in A B theoretically pervades the entire region around A B to infinite distance, with decreasing intensity. The same is true of the created strains. It is quite impossible to picture graphically or even mentally the exact mechanism of the disturbance so the "link mechanism" shown above is resorted to. It should be mentioned that the medium strained as explained above is supposed to be the ether, and the electromagnetic wave requires the ether for its propagation.

The mechanism explained above can be applied to a single vertical wire antenna as shown in Fig. 65 . The flux lines C in this case are set up by the sheet of displacement current A B $-A^1$ B^1 in the medium between the antenna and ground. The Fig. is not completed for a cycle on account of complication. The loops of electric strain in this case are not complete but terminate in the earth. They are closed through their images as shown by the dotted lines. The directions of flux and strain should be noted. The flux line D may be imagined to rotate around M N to form a closed-end-hollow cylinder of created strain. Here again D is not simply a small loop enclosing C but extends over large area. As the distance between adjacent positions of electric strain in space is one-half wave length, $\frac{\lambda}{2}$, the width of the loop of strain may be considered to be $\frac{\lambda}{2}$ as shown. The single line loops show successive strain loops created while the small circles show end on views of the created loops of flux as the wave progresses. Compare this Fig. with Fig. 7 in Chapter II. It must be remembered that the antenna oscillates periodically and the successive fields of flux and strain are continually being created in phase with the preceding fluxes and strains so as to reinforce the disturbance and keep it constant. This creates an undamped wave. If the oscillation of the antenna is damped the successive disturbances will have the same rate of decrease in intensity as that of the oscillation. Maxwell showed that the directions of progress of the wave is as shown by the heavy arrows and the speed of progression equals the velocity of light. The waves spread out equally in all directions around the antenna and parallel to the earth.

The student should be again cautioned about the various devices used to explain an electromagnetic wave. While the above explanation is not perfect it has advantages over those used by some writers. For instance, some authors explain that when the end of the line of electrostatic strain stretching from antenna to earth passes down to earth with the moving charge a closed loop of strain is formed which then moves outward with the velocity of light, 3×10^8 meters per second, and that the magnetic field set up expands as it moves. There are several absurdities about this explanation, the first being that no reason is apparent why the loop of strain should move at all, and the second is the inability to explain on this basis why the magnetic field should expand.

V. Derivation of the Radiated Field.

Fig. 66 is an elevation of an "L" antenna of height h. At point P a distance d from the antenna there is a magnetic force due to the current in the antenna. This force is represented by a vector and the "intensity" or "potential" of the vector is called the "vector potential" of the current at P. This has no connection whatever with potential of a charged body, or a battery, it is simply an expression used in Vector Analysis. The vector potential A at point P associated with field at this point is

$$A = \frac{i^1 h}{d}$$

The field at P is radiated from the antenna, hence i^1, the current producing the field at P, is not present in the antenna at the time of production of the field and of A due to the time required for radiation. The time required for radiation is $\frac{d}{v}$, where v is the velocity of the wave, 3×10^8 meters per second. Then if i is the current in the antenna at the above instant,

and $$i = I_o \sin w\, t$$

$$i^1 = I_o \sin w(t - \frac{d}{v})$$

Then $$A = \frac{h\, I_o}{d} \sin w(t - \frac{d}{v})$$

The total magnetic field around the antenna is the line integral of A per unit area or the curl of A

That is $$H_t = .1 \text{ curl } A$$

The constant .1 must be used to establish connection between units of H_t and i. All that is necessary to determine H_t is to get an expression for curl A. For the case of the antenna the

expression for curl A becomes

$$\text{Curl } A = \sqrt{\left(\frac{\partial Z}{\partial X}\right)^2} = \frac{\partial Z}{\partial X} = \frac{\partial A}{\partial d}$$

then $$H_t = .1 \frac{\partial A}{\partial d}$$

H_t is of course perpendicular to the plane of h and d

Substituting

$$H_t = -\frac{h w I_0}{10cd} \cos w\left(t - \frac{d}{v}\right) - \frac{h I_0}{10 d^2} \sin w\left(t - \frac{d}{v}\right)$$

The first term of the right hand member represents the radiated field while the second term represents the induction field. This latter term is small when d is great. Neglecting this term the maximum value of H_t is

$$H_0 = \frac{h w I_0}{10 v d}$$

For effective current I the radiated field H is

$$H = \frac{h w I}{10 v d} = \frac{2\pi h_s I_s}{10 \lambda c d}$$

where λ = wave length = $\frac{2\pi V}{W} = \frac{V}{f}$

h_s = height of sending antenna

I_s = current in sending antenna

Knowing the value of the radiated field at P it is easy to derive the relation for the current in a receiving antenna placed at this point.

The voltage generated in a conductor depends upon the rate of change of the flux within the loop of the closed receiving circuit or the rate of cutting the lines of force of the field:

$$E = h_r \, H V \, 10^{-8}$$

where E is the generated e.m.f. in volts, where h_r = height of receiving antenna in centimeters, H is the field intensity and v is the velocity of the wave, or the rate of cutting. Since v is equal to the velocity of light, 3×10^{10} cm. per second,

$$E = 300 \, h_r \, H$$

When the receiving antenna is tuned to resonance the received current is

$$I_r = \frac{E}{R}$$

for $X_L - X_c = 0$

Hence

$$I_r = 300\ h_r\ H \tag{12}$$

where I_r is in amperes, h_r is height to flat top in cm. and H is the strength of the magnetic field in gilberts per cm. Substituting the value of H derived above and given in equation (11),

$$I_r = \frac{188\ h_s\ h_r\ I_s}{R\,\lambda_c\ d} \quad \text{amperes}$$

h_s, h_r d and λ_c are measured in cm., R in ohms, and I_s in amperes. If the distance d is taken in miles, and the heights and wave lengths in meters the equation becomes

$$I_r = \frac{117\ h_s^1\ h_r^1\ I_s\ F_1}{d} \quad \text{amperes} \tag{13}$$

The above deduction assumes an undamped wave. If the wave is damped with a logarithmic decrement δ' the received current will also be damped and equation (13) does not hold. For this case the right hand member of equation (13) must be multiplied by a correction factor F_2 where

$$F_2 = \sqrt{\frac{1}{1 + \frac{600 L \delta'}{R \lambda}}}$$

where L is the inductance of the receiving antenna circuit. For great distances another correction factor F_1 is used where

$$F_1 = \varepsilon^{-\frac{.000047d}{\sqrt{\lambda}}}$$

for transmission over sea water. This applies if d is 70 miles or more. Inspection of equation (13) would indicate that the greater the wave length the less the value of I_r. This would be true if it were not for the correction factors F_1 and F_2. F_1 is called the "absorption" factor and in order that I_r be large F_1 must have a large value and this means that λ must be larger.

For great distances this overbalances the influence of λ in the denominator of equation (13). The equation for F_1 has been determined empirically by the Bureau of Standards.

VI. The Received Current in a Loop.

The current received by a loop can be deducted by reasoning similar to that for the antenna. When the value of H radiated from a transmitting loop is to be derived it must be remembered that the radiated field at any point is the resultant of the opposing fields from the vertical sides of the loop differing in time phase at that point due to the distance between the vertical sides. Space cannot be given here to the derivation for loops, but the student is referred to the paper entitled "Radio Transmission" by Dellinger, Proc. A. I. E. E., Vol. 37, October, 1919. The above derivations for an antenna follow those in this paper. Some additional equations derived are as follows:

Antenna to loop -

$$I_r = \frac{1184\, h_s\, h_r\, l_r\, N_r\, I_s}{R\, \lambda^2\, d}$$

Loop to Loop

$$I_r = \frac{7450\, h_s\, l_B\, h_r\, l_r\, N_s\, N_r\, I_s}{R\, \lambda^3\, d}$$

l represents distance between vertical sides of the loop and N is the number of turns. s and r refer to sending and receiving. All dimensions in centimeters.

VII. Range of Stations.

By the use of the above so called "transmission formulae" it is often possible and worth while to estimate the range of a proposed station, the location of stations of certain given capacities, or the efficiency and range of a receiving station. The principal empirical factor in this determination is the received current necessary for satisfactory reception through atmospheric strays. The transmission formulae themselves are not rigorous, the factors being much affected by many things such as mountains, clouds, sunlight, local storms, reflection of waves from upper atmosphere, etc. John L. Hogan (Proc. I. R. E., October, 1916) has given an interesting table of the practical ranges of high power stations, this table being shown below.

Distance in kilometers	2000	3000	4000	5000
Distance in miles	1240	1860	2480	3100
Wave length, meters	4000	7000	10000	12000
Antenna heights, feet				
Transmitting	450	700	850	1000
Receiving	300	400	450	500
Antenna Currents				
Receiving-micro amps.	100	100	100	100
Sending-amperes	64	105	170	265
Sending antenna Resistance-Ohms				
Radiation Component	1.9	1.5	1.07	1
Total	3.5	3.0	2.5	2.5
Sending Power - K. W.	14.5	33	72	175

Experience has shown that for satisfactory reception in temperate zones a current of .0001 ampere is necessary in the receiving antenna. The required values of sending antenna current for the distances given are based on the assumption that undamped wave transmitters and regenerative receivers are used. For damped wave spark transmitters the values of sending antenna current would have to be greatly increased. The figures of the table represent good engineering practice at present. Assumption is also made that radiation takes place equally in all directions, as is the case for the U. S. Navy high power station antennas. The figures would be greatly modified for directive antennas. No figures upon the latter have been available up to the present time.

VIII. Coils and Antennas as Radiators.

It was pointed out in Chapter II that coils or loops are very inefficient as radiators as compared to antennas. This fact has entirely eliminated their use up to the present time as transmitters of radio energy. However, they are coming into wide use as receivers. It is practically impossible to send sufficient current through a transmitting loop to cause it to radiate as strongly as a small antenna, but it is now feasible to amplify the extremely weak currents is a small receiving loop so as to produce audible signals in the telephones. In fact a small loop about three feet square with a dozen turns will give louder signals when used with a multistage amplifier than a fair sized antenna will give with a single vacuum tube detector. The amplifier for this purpose employs what is known as radio frequency amplification in which four to seven tubes are connected in cascade as in an audio frequency amplifier with the important difference that the tubes are coupled through low impedance or radio frequency transformers instead of the high impedance iron core transformers used with audio frequency amplifiers. Very high resistances may also be used instead of the radio frequency transformers. It is now possible to receive signals a distance of 1000 miles from a one K.W. transmitter radiating at 200 meters, and the reception accomplished with a small three foot loop. The receiving circuit for this is described in the Wireless Age, February, 1920.

CHAPTER VII

RADIO TELEPHONY

I. The Simple Radio Telephone.

The simplest form of Radio Telephone consists of an antenna excited so as to radiate undamped waves with some means of varying the intensity of radiation to correspond with the voice waves. Such a device is shown in Fig. 67 . The alternator A excites the antenna so that undamped waves are radiated at a certain intensity depending partly upon the resistance of the voice transmitter T. If the resistance of the transmitter varies with the vibrating diaphram the intensity of the radiation is varied or modulated in like manner. It may easily be seen that the currents in a receiving circuit receiving the transmitted waves will vary in a like manner and the result is a radiophone system. Referring to Fig. 68 A represents the frequency of the generated oscillations, $\frac{1}{2\pi\sqrt{LC}}$; B represents the frequency and nature of the voice wave for some simple vowel sound. Since the intensity of the radiated wave is varied with the voice wave, the radiated wave will be of the form shown by C. A is the carrier wave (carrier frequency), B is the modulating wave, and C is the modulated wave.

II. Methods of Modulation.

Many methods of modulation have been experimented with, most of which have been unsuccessful. The method described above is very simple but offers one great difficulty. All of the radiation current must pass through the microphone transmitter. The heating of the carbon particles reduces the sensitivity greatly. Many types of resistance variation microphone transmitters have been devised in attempts to modulate comparatively large amounts of radiated energy by means of the small energy of the voice waves. A good historical account of such work will be found in "Radio Telephony" by Goldsmith. Microphones have been used in other ways as modulators and in order to make clear the principles of vacuum tube modulators one simple method will be described here although it is of no commercial value.. Referring to Fig. 69 the d.c. arc is the generator of sustained oscillations. When the microphone M is

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

spoken into the varying current in the primary circuit induces an electromotive force in the coil L which varies the resulting potential across the arc and thus varies the amplitude of the high frequency oscillations in the inductance and capacity of the antenna which shunts the arc. This is a radically different method of modulation from the one formally described, in that it depends for its effectiveness upon the potential generated in L within certain limits instead of direct modulation of heavy currents by resistance variation. This and other methods are open to the objection that they will only operate within certain ranges, the total modulating effect is small, and in most cases the modulation is not true due to characteristics of the circuits, and as a result the speech is distorted.

III. Vacuum Tubes in Radio Telephony.

As a generator of undamped waves required in radio telephone transmission the vacuum tube is very satisfactory for at least two reasons; first, there is no hissing or grating noise as with an arc or alternator, and a pure sine wave of carrier frequency is emitted; and second, effective modulation is easily and simply accomplished. Fig. 70 shows a simple form of vacuum tube radiophone transmitter.

The vacuum tube generator functions as described in Chapter V owing to the capacitative coupling between plate and grid circuits by means of condenser C_3. It is very similar to the regenerative receiving circuit of Fig. 58 . When the microphone is spoken into the potential of the grid is varied by the induced e.m.f. in the secondary of the speech transformer or telephone induction coil. Thus the plate current is easily varied by the vibrations of the voice and this variation superimposed upon the periodic variations of plate current while the tube is generating. The result is modulated waves emitted from the excited antenna. Another arrangement of the circuit is shown in Fig. 71 making use of direct coupling to the antenna.

The method of modulation shown above, although simple, is limited in its range due to the varying impedance introduced, and to the fact that the radiation cannot be doubled nor reduced to zero, which should be possible with a very efficient modulating system. The circuit shown in Fig. 72 has this desirable feature and has been developed for Signal Corps and Aeroplane use and for the Navy. Two transmitting tubes are connected in parallel as shown in the Fig. and plate current is supplied to each by battery B. L_c is a choke coil of very high inductance so that variations of current at radio or audio frequencies cannot occur, hence the supply current is constant. Tube M is the modulator tube, and tube G the generator of radio frequency currents in the circuit to the left of G. Normally each tube takes the same plate current, or half the constant output of the battery. If the grid potential of M is momentarily positive the resistance of the circuit through tube M is very low and all of

the battery current will pass through M and O will cease to generate, hence the radiation is reduced to zero. If the grid potential of M is negative the resistance of M may be so high as to reduce its plate current to zero so that the plate current of G and hence the radiation would be nearly doubled. L_R is a radio frequency choke coil which keeps the radio frequency potential variations from tube M and prevents it from oscillating. If the power to be modulated is large an additional tube may be used as an amplifier, the secondary of the speech transformer being connected in series with the grid, and the plate or output circuit of the amplifier tube connected through another transformer to the grid of the modulator tube in Fig. 72 or from grid to filament in Fig. 71 .

IV. Typesof Radio Phone Transmitters.

For high power transmission work the generator must consist of many high power tubes in parallel, and even amplifier tubes are used to amplify the generated modulated radio frequency currents. During the experiments in 1915 when radio telephone communication was accomplished from Arlington to Paris three hundred high power tubes in parallel were required, producing a current of about 75 amperes in the antenna.

One ingenious method of radio phone transmission without the use of vacuum tubes, and which is quite successful is shown in Fig. 73. This system makes use of the high frequency alternator and the modulation is accomplished by means of the so called "magnetic amplifier" invented by E. F. W. Alexanderson. The magnetic circuits and windings are so arranged that a variation of current through the microphone results in a varying shunt impedance across the terminals of the alternator. This is accomplished by winding the two parallel coils B and C on legs of the iron core shown in the Fig. so that when radio frequency currents flow through them fields are set up in the direction shown by the arrows so that no radio frequency potentials are generated in coil A. The current in coil A from the battery magnetizes the iron core to nearly saturation point and the permittivity of the iron core of coils B and C will depend upon current in A, and hence the reactance of each coil will depend upon relative directions of m.m.f.s. produced by currents in A and B or A and C. Varying the current in A by means of microphone T will also cause impedances of B and C to vary in proportion. This device has been successfully used to modulate fairly large amounts of power, however, not without some distortion of speech due to the lag of magnetism or hysteresis effect. Also considerable power is wasted due to coils being shortcircuited, and hence having audio frequency currents generated in them. There is also some circulating radio frequency current. By properly shunting and separating different parts of the circuit with condensers great improvement is obtained. The hysteresis effect is also eliminated by cross magnetizing the core by another winding connected to a source of low frequency a.c. The purpose of this is to keep the molecules of iron in

continuous motion. The amplifier and its modifications have an advantage over the vacuum tube system for large amounts of power, as the latter system becomes complicated and expensive. The Alexanderson and the Hartley amplifiers are fully described in "Radio Engineering Principles" by Lauer and Brown, p. 245.

The fundamental circuit of the aeroplane radiophone was described in a previous paragraph. The actual circuits were very complicated due to the fact that a receiver with a two step amplifier was included in the same box, the receiving tubes excited from the same source of d.c. voltage and a single multipole switch used to change over from talking to listening. The plate and filament circuits were all supplied from a double mound d.c. generator driven by a small propeller. This generator delivered 25 volts for the filaments and 250 volts for the plate circuits, and in order that the frequency of the commutator would not produce noise in the telephone receiver a special combination of choke coils and condensers was provided with the addition of a two element rectifying tube connected in shunt with the generator. This arrangement is called a "filter".

The De Forest Radio Phone is so arranged that it can be used with the sixty cycle lighting circuit voltage as a source of plate voltage and filament current. For plate voltage the 110 volts a.c. is stepped up to 500 volts by means of a transformer and rectified by means of two Kenotron tubes (two element tubes) into a pulsating d.c. e.m.f. By means of a filter the plate currents are rendered constant. Four Marconi V. T. tubes in parallel are used. It is said to be able to transmit speech twenty miles.

V. Receiving Apparatus for Radio Telephony.

The waves used in radio telephony are undamped, but vary in intensity, therefore the high frequency currents in the receiving apparatus will also vary in intensity with the voice waves. If a crystal detector and telephone receiver are connected into the circuit the currents will be changed to unidirectional pulses and the receiver diaphram will pulsate with the speech variation of the currents and can be recognized and understood. A simple vacuum tube detector properly adjusted can also be used. The regenerative or beat receiver would distort the speech and could not be used. Amplifiers may be used with either vacuum or crystal detector, and must be arranged to operate as near as possible on the straight part of their characteristic curves for true amplification. The high frequency resistance of the receiving circuit must be as great as or greater than the transmitting circuit for the following reason. Let Fig. 74 represent an incoming wave of the form shown due to modulation. This is similar to a damped wave and if the decrement of the receiving circuit is low this wave will persist longer than it should and the resulting current in the receiving circuit will not be correctly modulated resulting in distortion

of speech. Usually receiving circuits are of higher resistance than transmitting circuits and this difficulty is not met with.

VI. Duplex Radio Telephony.

In the previous treatment of Radio Telegraphy it was assumed that the transmitting and receiving apparatus were separate, and that a user of such a telephone would have to throw a switch when through speaking which would connect in the radio receiver so that he could listen for a reply. This is unsatisfactory, as anyone will realize who has tried it for the reason that if both parties attempt to speak at the same time neither is heard, and then may listen simultaneously, and not hearing anything may give up attempting to communicate. The most difficult problem of Radio Telephony is the perfection of a practical means of simultaneous transmission and reception. Such an arrangement means that a person would be able to hear the other party while he himself is speaking. The principle of such a system is shown in Fig. 75 . With this apparatus the microphone is spoken into and the radiations of the undamped wave generator will be vocally modulated transmitting speech but the receiving circuit will not be affected. The antenna is divided into a sending and a receiving portion by the Insulators as shown. The transformer T is used to create a potential of opposite phase to the potential of the sending antenna. This negative potential is impressed on the receiving antenna through the exposure condenser E. This impressed potential is adjusted to counterbalance exactly the direct effect of the sending part of the antenna upon the receiving part leaving the latter undisturbed and responsive to incoming waves from the other station. F is called a frequency trap and must be used as the phase relation of the transformer is not exactly 180° D may be a simple vacuum tube detector, or it may be a combined detector and amplifier. The distant station has similar apparatus and ordinary conversation may be carried on. A recent treatise on this development may be found in an excellent paper by Alexanderson, "Simultaneous Sending and Receiving", Proc. I. R. E., August, 1919.

CHAPTER VIII

RECENT DEVELOPMENTS IN RADIO ENGINEERING

I. High Speed Transmission and Reception.

The number of transoceanic stations that can operate satisfactorily across the Atlantic ocean is limited. The wave lengths now used range from 12,000 to 17,000 meters, the best engineering practice indicating that these two wave lengths form the lower and upper limits for efficiency. The wave lengths of the various stations must differ by a certain amount so as to not cause interference, and this means that the number of stations is limited to five or six. There are five operating at present and these must handle the large amount of European-American business. In order to do this, some of the stations have resorted to high speed transmission at the rate of 75 to 100 words per minute. This is accomplished by making perforated tapes of the messages to be sent, and using the tapes to operate a high speed relay which controls the transmitted energy. The messages are received upon phonographic recording cylinders with the aid of two or three stage amplifiers. The records made at the high speed are then put into phonographs and the message transcribed at thirty words per minute. This makes it possible to handle three times the volume of business that could be handled by hand key transmitting. The Marconi high power transoceanic stations have adopted this method.

II. High Power Stations.

The Marconi trans Pacific stations are designed to maintain almost continuous communication between the United States and Japan. The system consists of three stations, one located at Bolinas, California, one at Kahuku, Hawaii and the third at Funibashi, Japan. The station in Hawaii is used as a relay station and during periods when weather is bad all messages to and from Japan must be relayed. The wave length used is 17,000 meters, and the undamped waves are generated by the rapid successive discharging of the condenser in the primary circuit by a synchronous rotary gap. When the wave length is very long the antenna oscillates at a comparatively very low frequency. This method of producing oscillations was explained in Chapter IV. The power is supplied by 350 K. W. alternators, each station having two alternators installed so as to maintain one machine

ready for use at any time. The antenna is of the Marconi directive type, a long inverted "L" antenna 450 ft. high and with a horizontal length of two miles. The "L" of the antenna at Bolinas extends in a direction from the transmitting station which is away from Hawaii. This means that the directive property is in the direction of the Hawaiin station. Two transmitting antennae are provided at the Hawaiin station. Each station has a smaller receiving antenna. A large amount of commercial business is handled by these stations and in order to accommodate the traffic high speed transmission and phonographic cylinder reception are used.

Nearly all of the high power U. S. Navy Stations are of the Poulsen arc type, Poulsen Federal System. The radiator consists of flat topped antennas swung between either two, three, or four towers, depending upon the size of the station. The high power arc stations are located at Annapolis, Md., Arlington, Va., San Diego, Cal., Pearl Harbor, Hawaii, and Cavite, Phillipine Islands. The station at Annapolis was finished during the war. The following are its main features: Antenna system on four 650 foot towers, duplicate 350 K. W. arc converters (this is the term given high power oscillating arcs), duplicate 400 K. W. 1430 volt d.c. generators driven by 600 H. P. three phase induction motors, and an antenna current of 400 amperes, maximum rating. The operation of the station is by remote control, the operator and sending key being in the Navy Department office in Washington. As previously explained signals are sent by changing the wave length of the emitted wave. In the Annapolis installation this is accomplished by short circuiting a single turn loop which is closely coupled to the antenna loading inductance. (See Wireless Age, December, 1919).

The Arlington station has three towers, two of which are 450 feet high and the third 650 feet high. This station contains four separate transmitting sets, a 100 K. W. arc, and a 100 K. W. spark (damped wave) transmitter, and a 35 K. W. and 5 K. W. spark transmitter. The antenna current in the case of the 100 K. W. sets being 100 amperes. This and the 100 K. W. spark sets can be operated by the operator in Washington, a few miles distant. The main features of all the larger Navy stations are given in the following Table

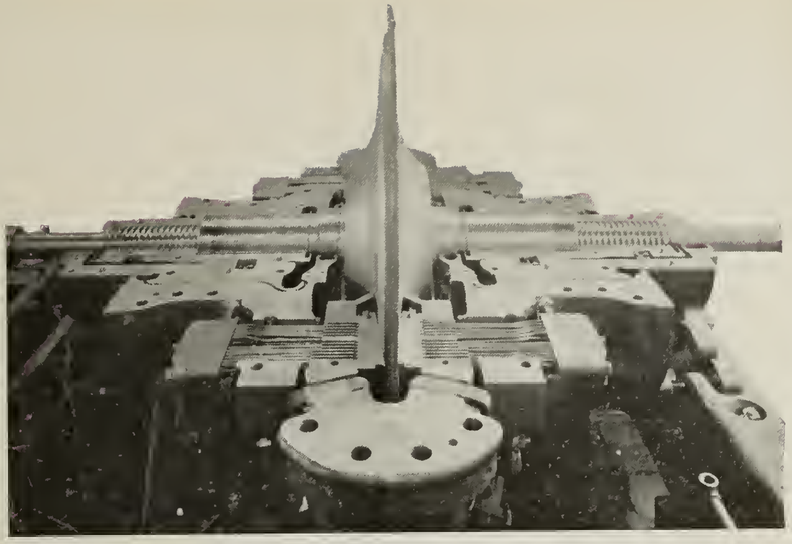
Name of Station	Call Letters	No. and arrangement of towers	Power Consumed by arc in K. W.	Antenna current amperes
Annapolis	NSS	4 - square	350	400
Arlington	NAA	3 - triangle	100	100
Cavite, P. I.	NPO	3 - triangle	350	200
New Brunswick	NFF	Directive "L" Antenna	Alternator	
Pearl Harbor	NPM	3 - triangle	350	200
San Diego	NPL	3 - triangle	200	150

The new Navy station at New Brunswick, N. J. employs a 200 K. W. Alexanderson high frequency alternator of a frequency of about 22,100 cycles (13,600 meters). The antenna is known as a multiple directive type and the antenna and connected circuits are shown in Fig. 76 . Due to the presence of the shunt inductances to ground the radiating efficiency is high while the ohmic resistance is low. The antenna current is 600 amperes. The total energy consumption of the antenna is 180 K. W. while the energy radiated is 25 K. W., radiation resistance is .07 ohms. 25,000 watts = $(600)^2$ x .07. The radiation efficiency is thus 14 per cent. One difficulty in the use of an alternator is encountered in any variation of speed of the machine. The wave length is affected by a slight variation of speed. A special control is provided in this station to maintain the speed as nearly constant as possible. A complete description of this station is found in Proc. A. I. E. E., October, 1919, p. 1077. Accompanying cuts show the alternators used in this station.

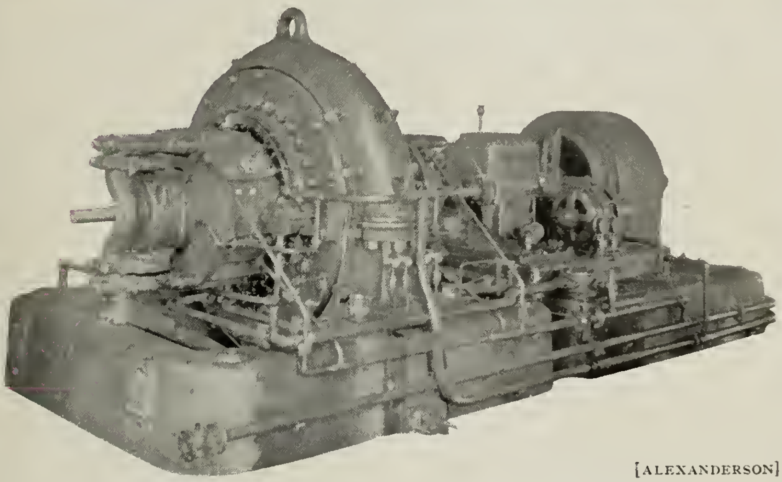
III. The Weagant Static Eliminator.

In a paper by Roy A. Weagant, Proc. I. R. E., June, 1919, the author describes extensive experiments upon the origin, nature, and elimination of strays; and describes a very successful device for the complete elimination of strays and strengthening of the signals. The perfection of this device resulted from the discovery that most of the strays are propagated vertically downward in the form of induced potentials on the antenna causing it to discharge to ground through the receiver. The device for eliminating the strays will be better understood by a study of Fig. 77.

A and B are single turn loops of dimensions shown, and are situated one-half wave length apart for the particular signal received. If the signal wave approaches the loops from right to left in the plane of the paper the current in loop B will be maximum positive at the instant those in A are maximum negative and vice versa. In other words, the currents in the loops will be 180° out of phase. The currents in the loops due to strays will be in phase due to the fact that the strays are propagated vertically downward as stated previously. Hence, if coils L_5 and L_7 are rotated so that the inductive effect of the static currents in each is neutralized the inductive effect of the signal currents in L_5 and L_7, being 180° in time phase will be additive. The result is that the induced currents in coil L_c will be those due to signal currents only, and will be twice the strength of those that would be generated by L_5 or L_7 alone. The stray currents in L_6 are zero because L_5 and L_7 were rotated until their fields due to stray currents neutralized. It is claimed that loud crashes in the receiver were reduced to a faint murmur when the second loop is cut into the circuit while the signal strength is actually improved, although not actually doubled

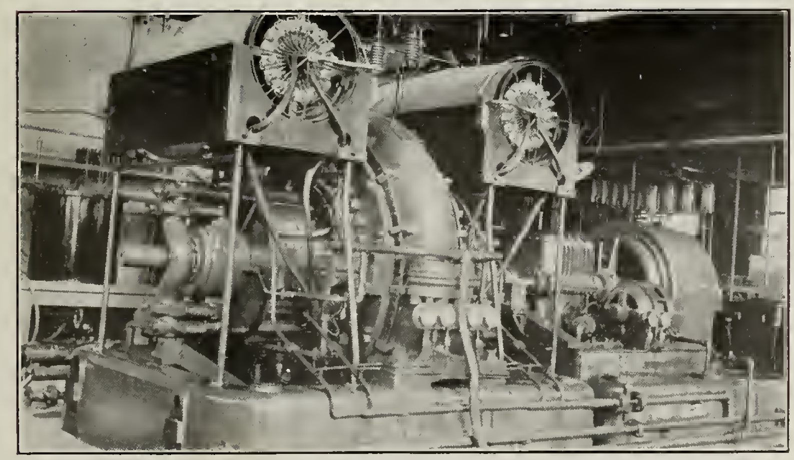


[redacted]. [redacted]—200-Kw. High-Frequency Alternator



[Alexanderson]

[redacted]. [redacted]—200-Kw. High-Frequency Alternator



[redacted]. [redacted]—200-Kw. Alternator Set as Installed in the Naval Radio Station, New Brunswick, New Jersey

in strength. The distance from A to B may be only one quarter wave length with a theoretical increase in signal strength of 41%. The three rotating coils are known as a "goniometer" which is shown in the Fig. 78. If the inductive effects of L_5 and L_7 do not exactly balance L_6 may be rotated so as to be in the resultant field. The tuning out of strays requires adjustment of all three coils. The arrangement and functioning of the receiving tube is self evident. There are many modifications of this scheme, all of which are described in the above paper or in the April and July, 1919 numbers of the Wireless Age.

IV. Direction Finders - Radio Compass.

In Chapter II it was shown that the loop radiates maximum signals in directions in the plane of the coil, and practically zero radiation is obtained in a direction along the axis or perpendicular to its plane. The same property is found for the loops as a receiver. Signals coming in the direction of the plane of the loop will be a maximum while if the loop is rotated through an angle of 90° the signals received will grow very faint. The variation in intensity of the received signal for different directions is shown in Fig. 79 . A B represents a plan view of the loop which rests with its plane vertical. Signals from direction D_1 are minimum while those from D_2 are maximum. Obviously a small variation from D_1 produces a more noticeable change in signal than a like variation from D_2. Hence when the loop is used as a direction finder the position of minimum signal is found. This position can be found within a half degree. The Signal Corps loop used as a radio compass is in the form of a flat spiral coil with its plane vertical and rotating about a vertical axis. Radio Compass Stations are installed at points along the Atlantic Coast. If the directions of the signals sent out by a ship are determined simultaneously by two radio compass stations, the ships position may be quickly determined by triangulation, knowing the distance between the compass stations and their position. A ship can now obtain its position by calling a Naval station and asking for a determination of its position. The Naval station then advises the compass operators by telephone at three compass stations who listen to the ships signals and determine the directions of the latter. From this data the Naval station determines the ships position and advises the latter by radio message.

For aeroplane direction finders the minimum signal method cannot be used because of noise. Two loops are set at right angles one of which is cut in series with the other for various positions of the two, and at a certain position the added signal strength will be very marked.

V. Alexanderson Barrage Receiver.

The "Alexanderson Barrage Receiver" is an ingenious modification of the Bellini Tosi antenna, and phase rotating or shifting devices so that signals from a certain direction may be

received while those from another station in a different direction may be completely balanced out. By using this device it was possible to receive from the Marconi station in Wales on 14,000 meters while New Brunswick was transmitting with a wave length of 13,600 meters not more than three miles distant. For a full discussion see Proc. I. R. E., August, 1919, p. 363.

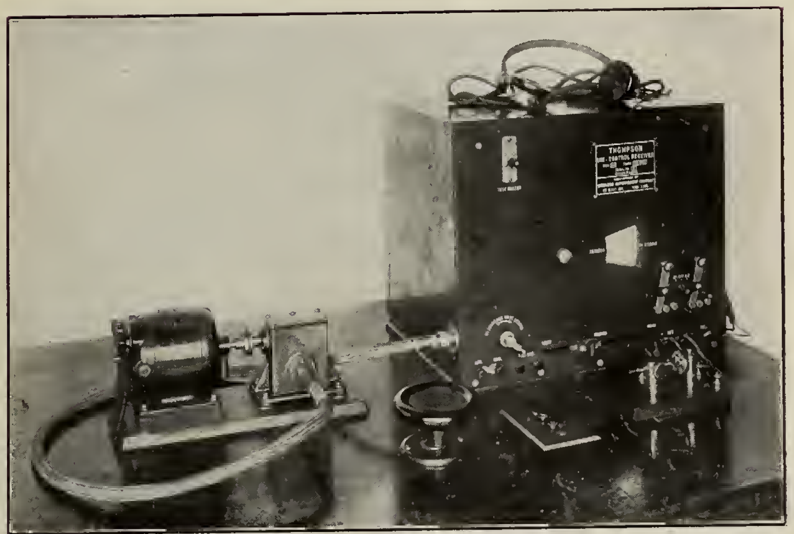
The "unicontrol" receiver developed by the Cutting and Washington Company is used on ship board. By its aid an operator can hear calls on many wave lengths. The tuning of the receiving circuits is varied through the range of wave lengths for which the receiver is designed. The variation is periodic, the apparatus being driven by a motor. The operator listens and watches a rotating dial. If he hears a signal when the dial indicates 600 meters, for instance, he can stop the motor and set the dial stationary at 600 meters and listen. This aids an operator in picking up distress calls. See cut next to this page.

VI. Recent Experiments in Radio Telephony in 1915 and in 1916.

The most remarkable accomplishment in radio telephony was that of the Western Electric Company's engineers in the winter of 1915. An immense vacuum tube transmitter was erected in the U. S. Navy station at Arlington, Va., and radio telephone messages were sent out which were heard distinctly in the Eiffel Tower station in Paris. The message was heard simultaneously in the U. S. Navy station at Honolulu. The distance covered was 3000 miles to Paris and 6000 miles to Honolulu. For the transmitter a vacuum tube generator of many high power tubes was used and the modulating currents were amplified by additional high power tubes. Still more high power amplifier tubes amplified the modulated radio frequency output of the generator tubes. A total of three hundred tubes were used in the antenna. The antenna current was about 75 amperes.

The radio transmitter at Arlington was connected through regular land telephone toll offices to the executive office of the American Telephone and Telegraph Co. in New York. Mr. Carty talked to Arlington by wire, and the resulting voice currents were used to modulate the output of the high power transmitter at Arlington, as in the previous experiment. The radio phone message was received at the U. S. Navy Station at San Diego, California, the amplifier output circuit of the receiver being connected to the long distance wire telephone leading to New York. Vacuum tube repeaters were used in this line and the received radio message was automatically repeated over the land wire to New York. Officials listening on the wire from San Diego by way of San Francisco heard the words and recognized Mr. Carty's voice. This demonstrated the practicability of inter connecting radio phone stations with wire telephone lines.

Secretary Daniels was enabled during the recent experiments of the Navy to sit at his desk and speak to commanders



Cut Showing the "Unicontrol Receiver."

of the various vessels of the Navy while the latter were more than half way across the Atlantic. Telephone engineers are hopeful of developments in the future that will make it possible for a person at his home or office to call, and communicate verbally with any desired person who at that time is on board ship; or a person out at sea may call his family at his home to advise them of a pleasant voyage, and ask for news from home.

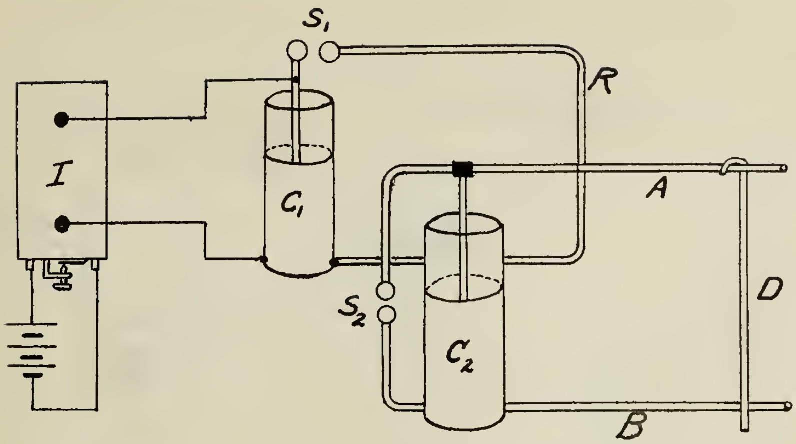


Fig 1.

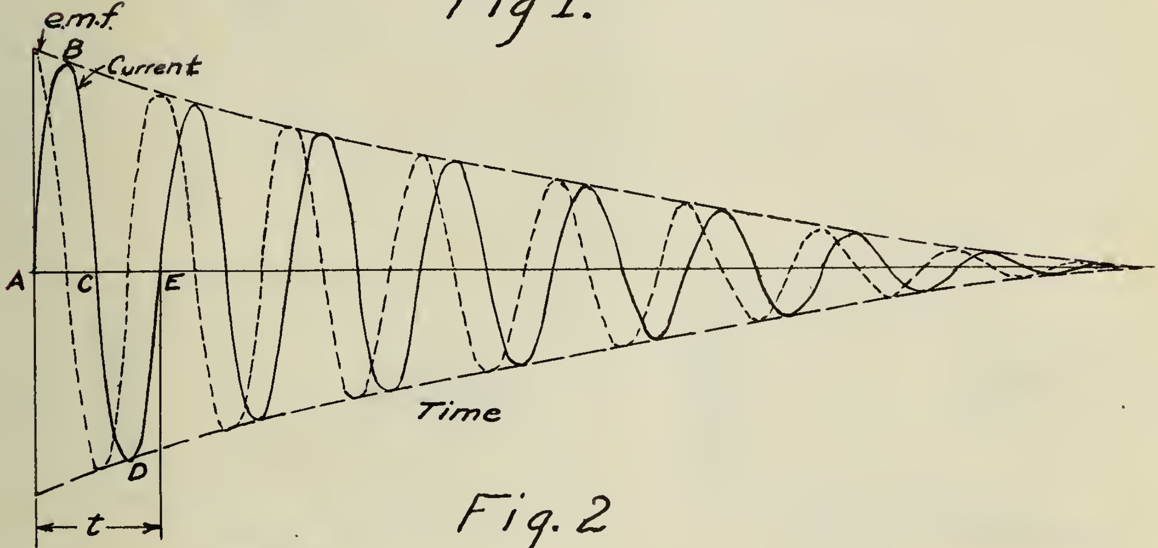


Fig. 2

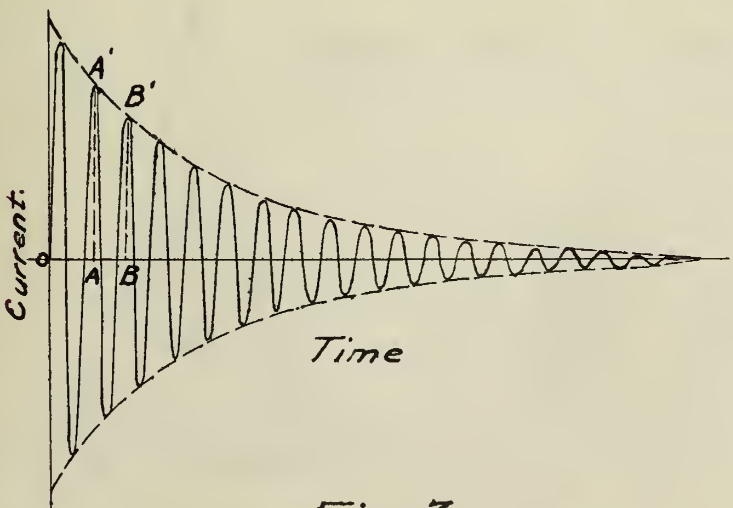
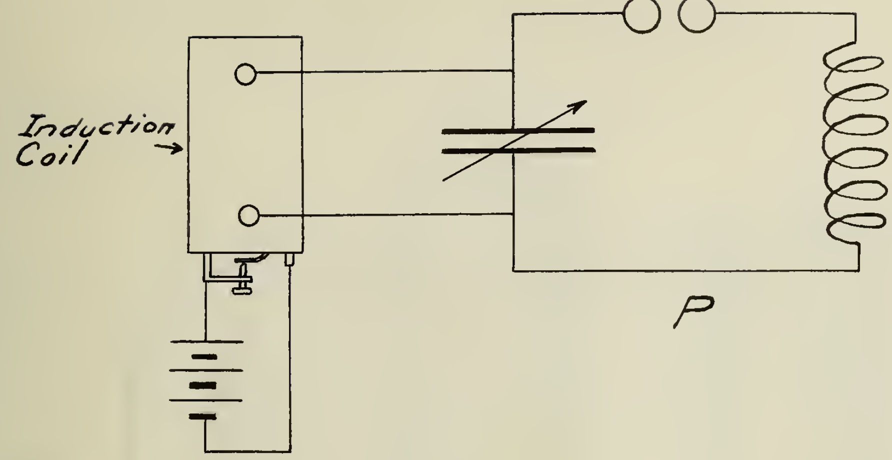
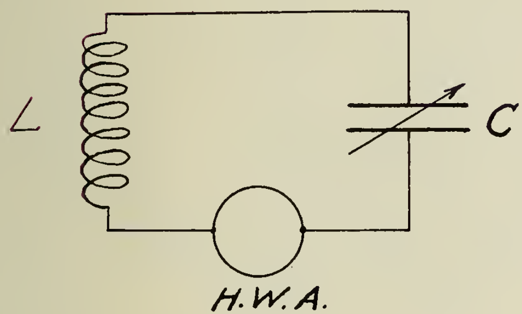
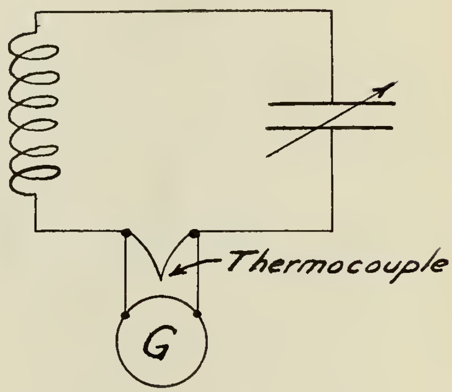


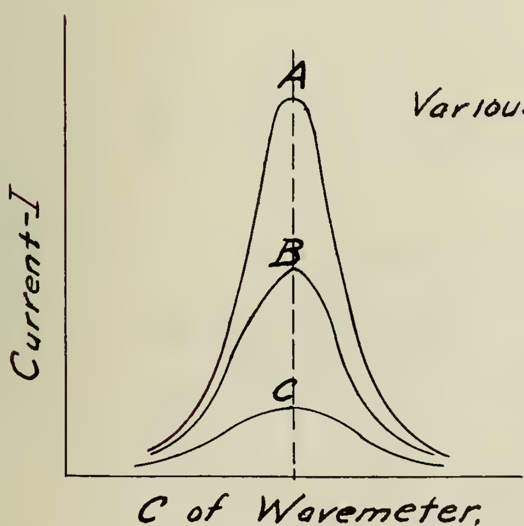
Fig. 3.







Various Forms of Wavemeters.



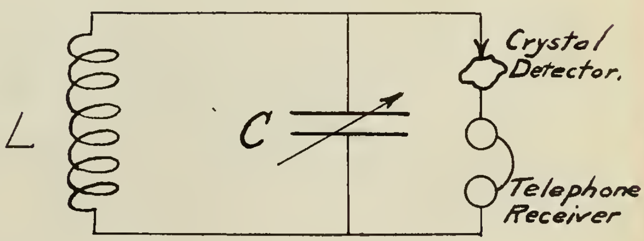


Fig. 4.

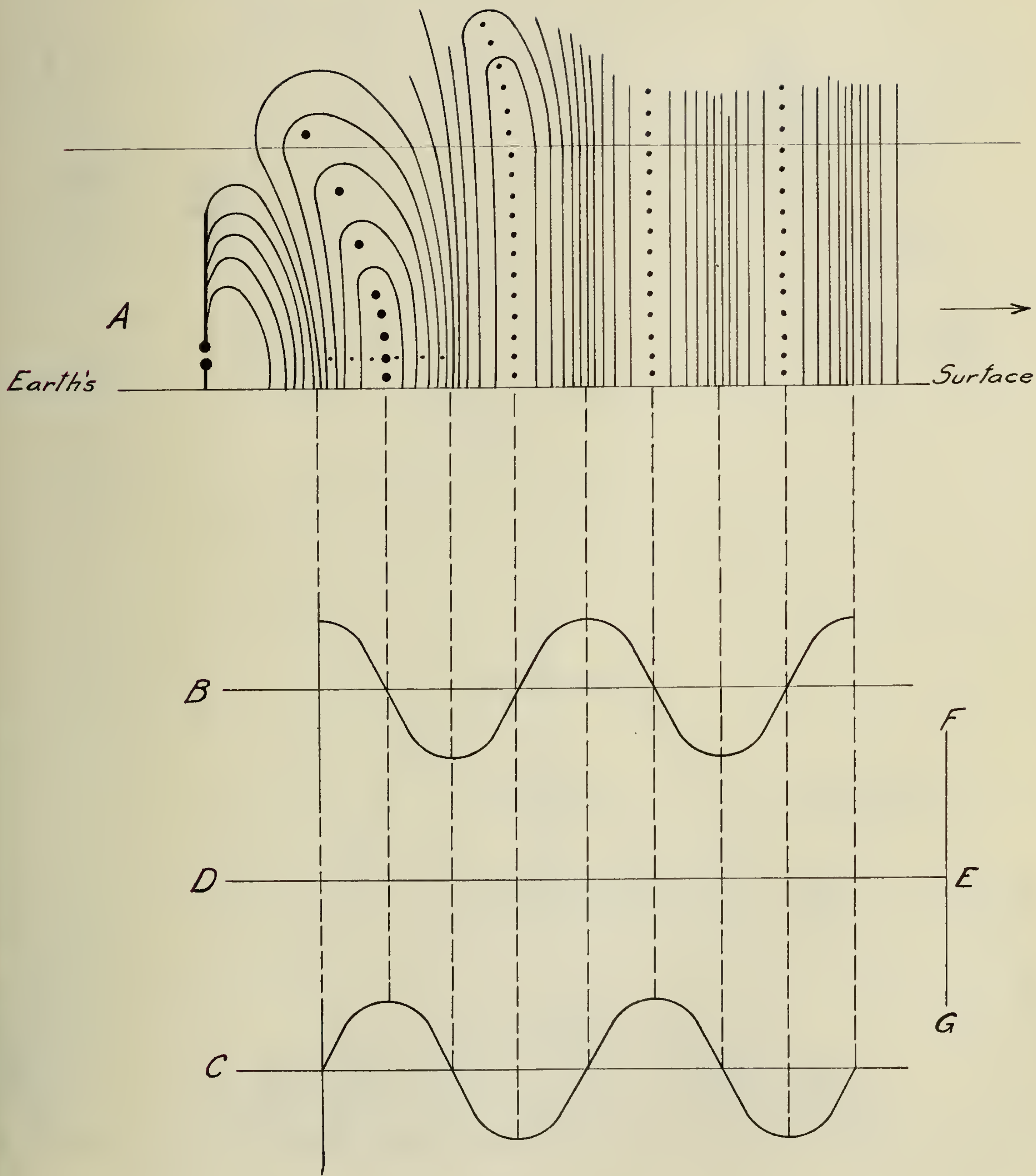


Fig. 8.

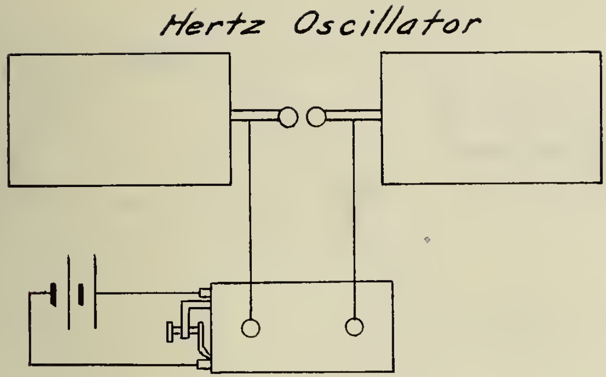


Fig. 5.

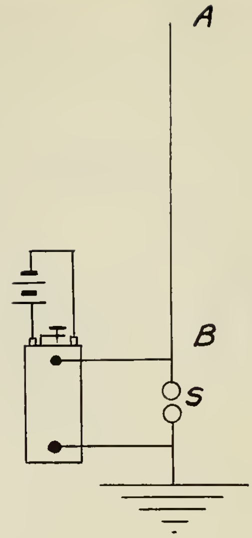


Fig. 6.

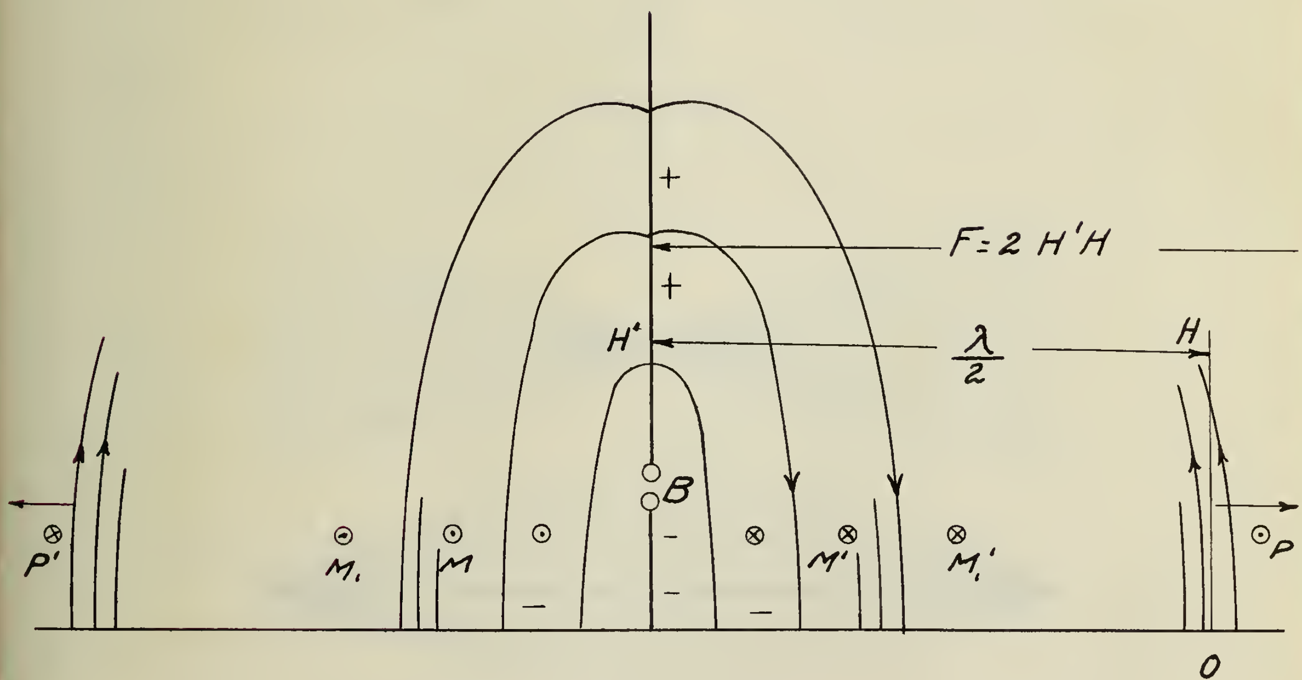


Fig. 7.

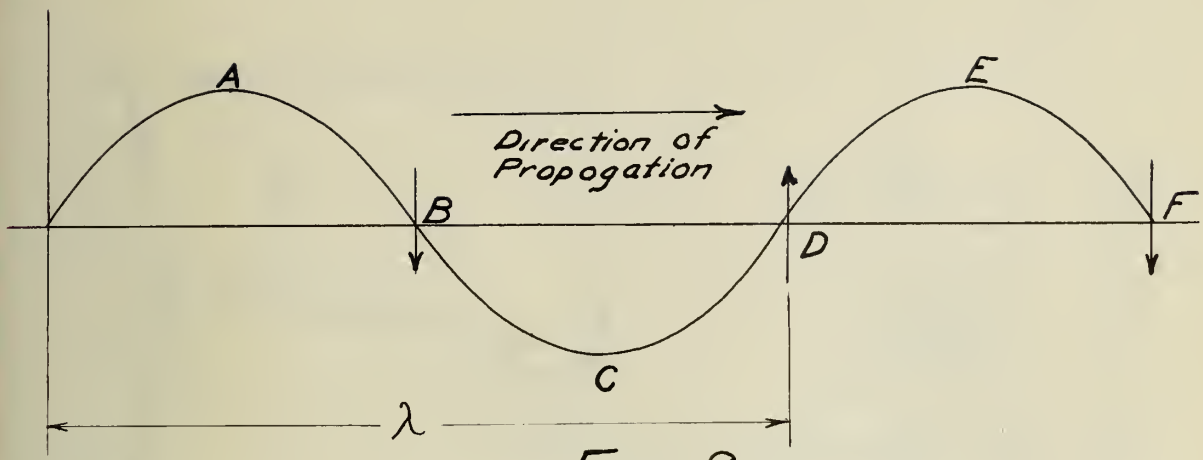


Fig. 9

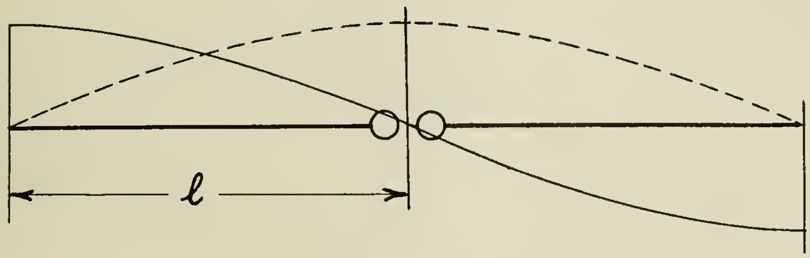


Fig. 10

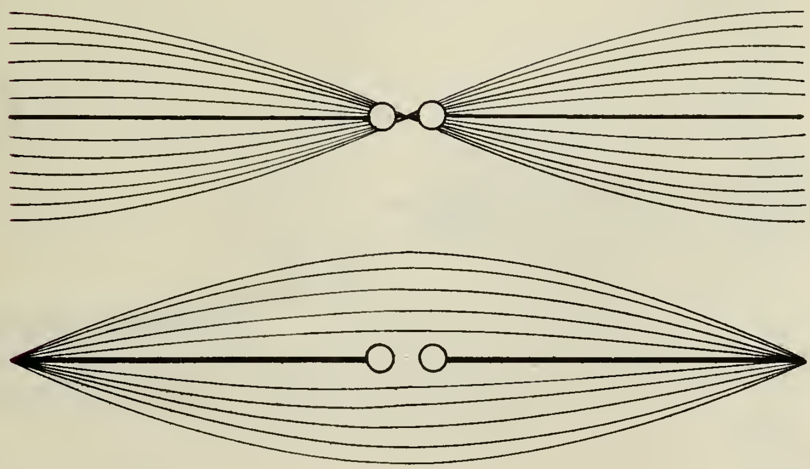


Fig. 11.

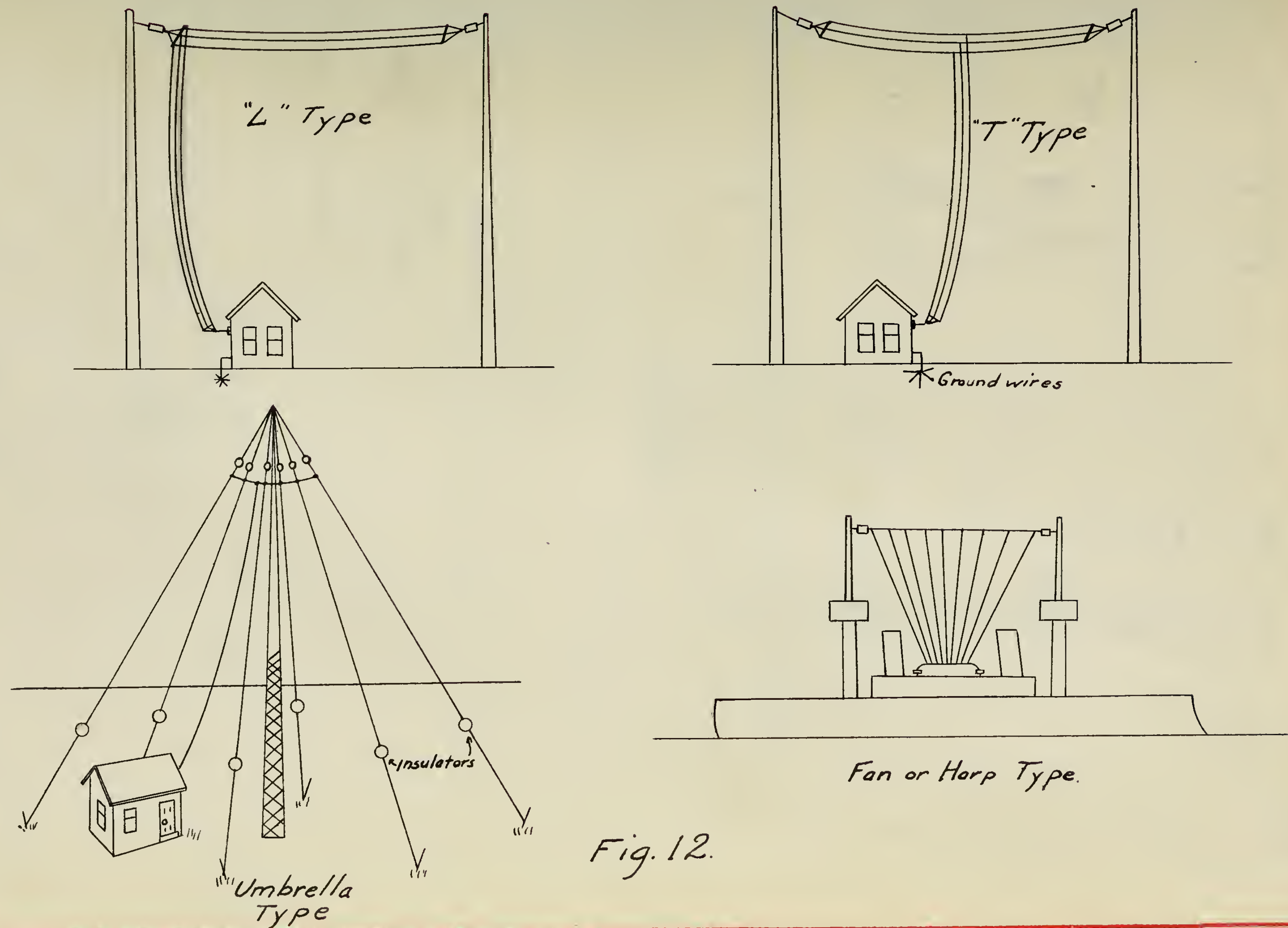

"L" Type
"T" Type
Ground wires
insulators
"Umbrella Type
Fan or Harp Type.

Fig. 12.

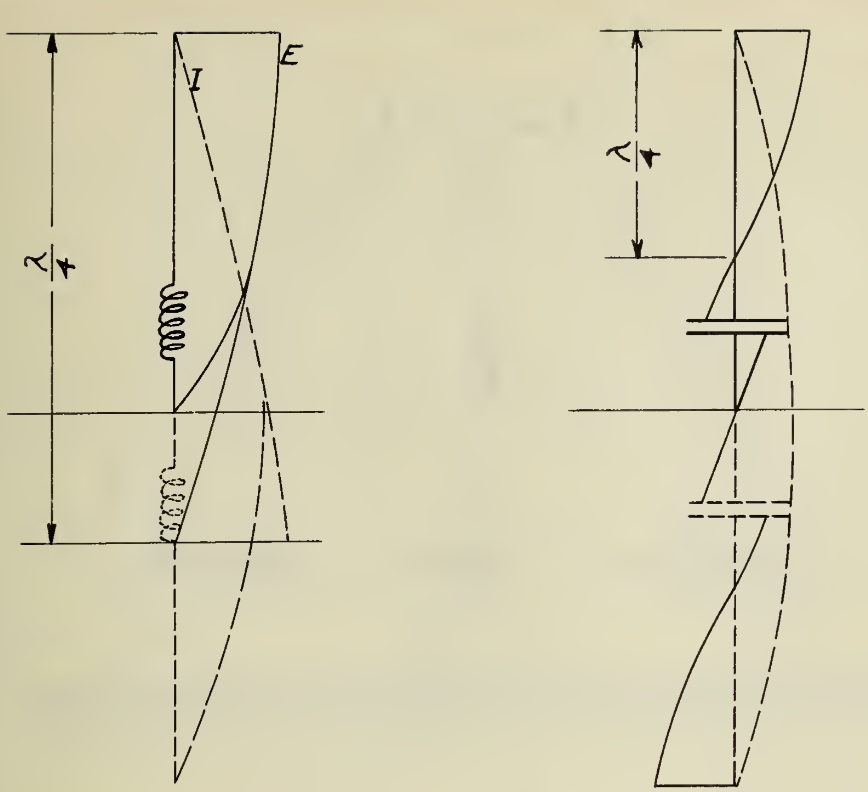


Fig. 13.

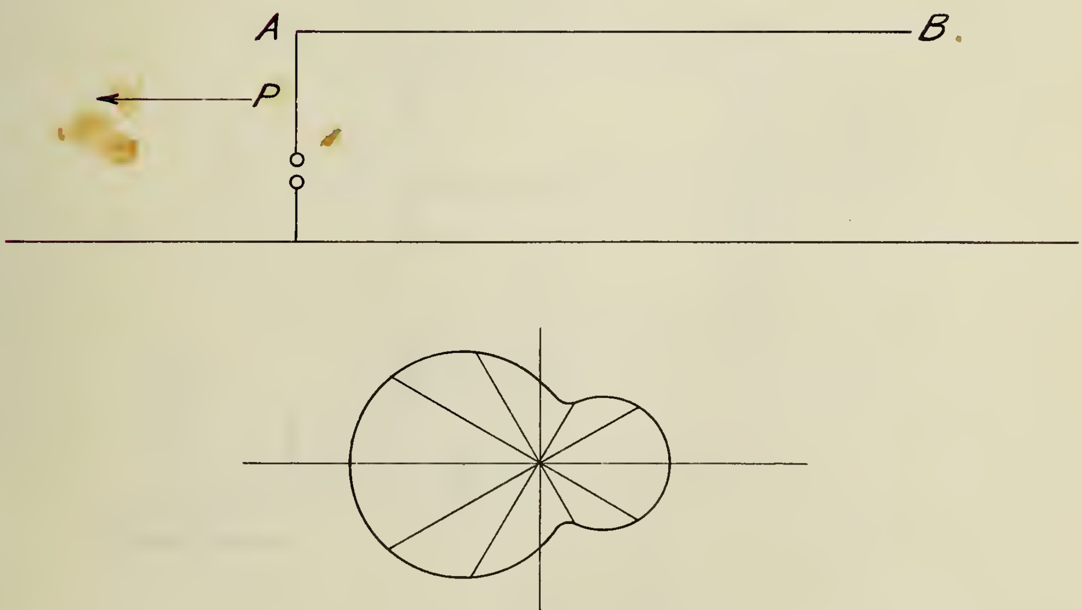


Fig. 14.

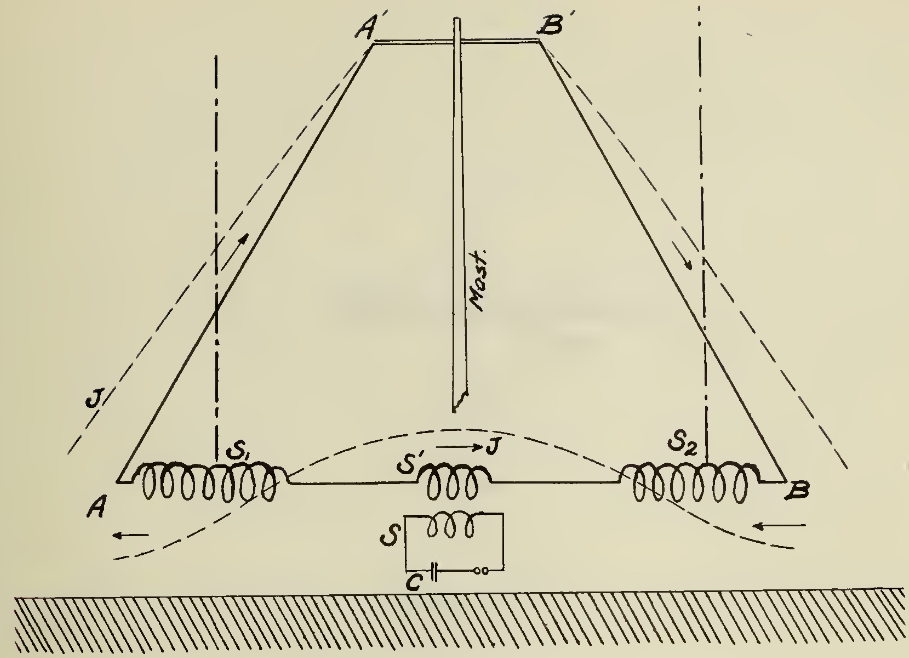


Fig. 15.

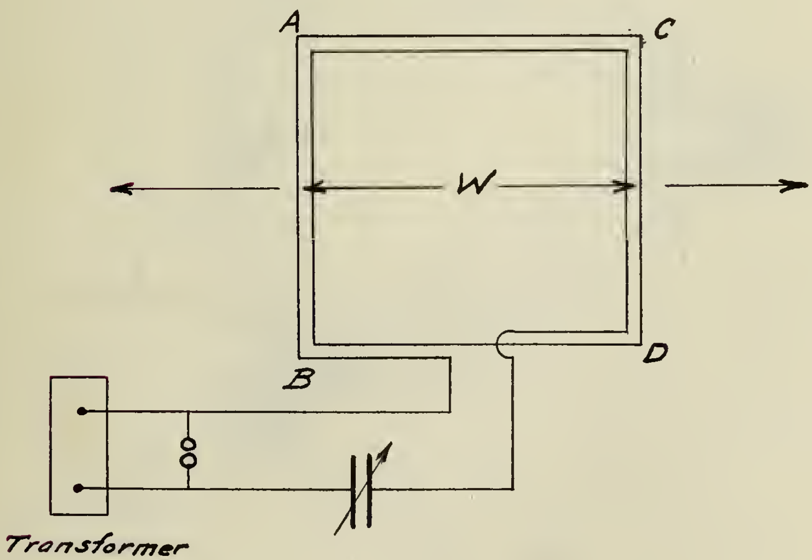


Fig. 16.

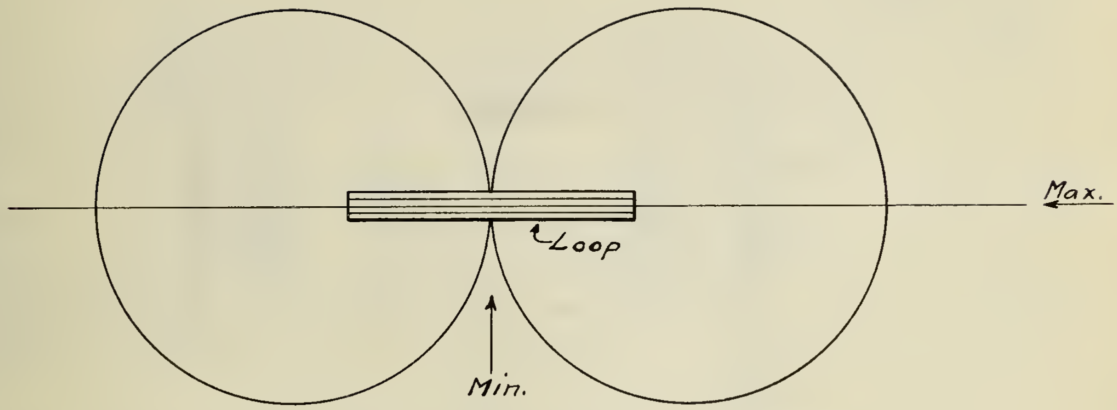


Fig. 17.

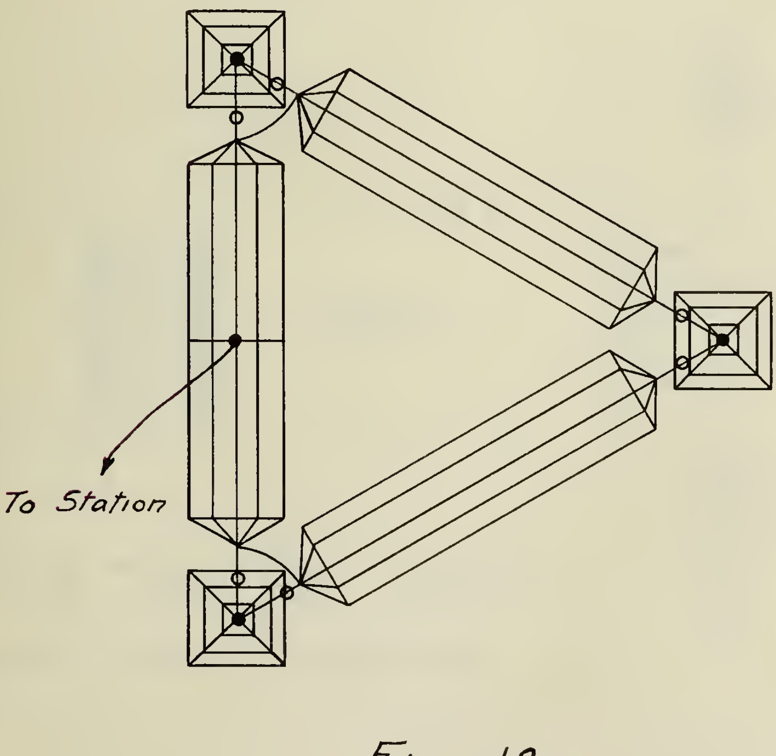


Fig. 18.

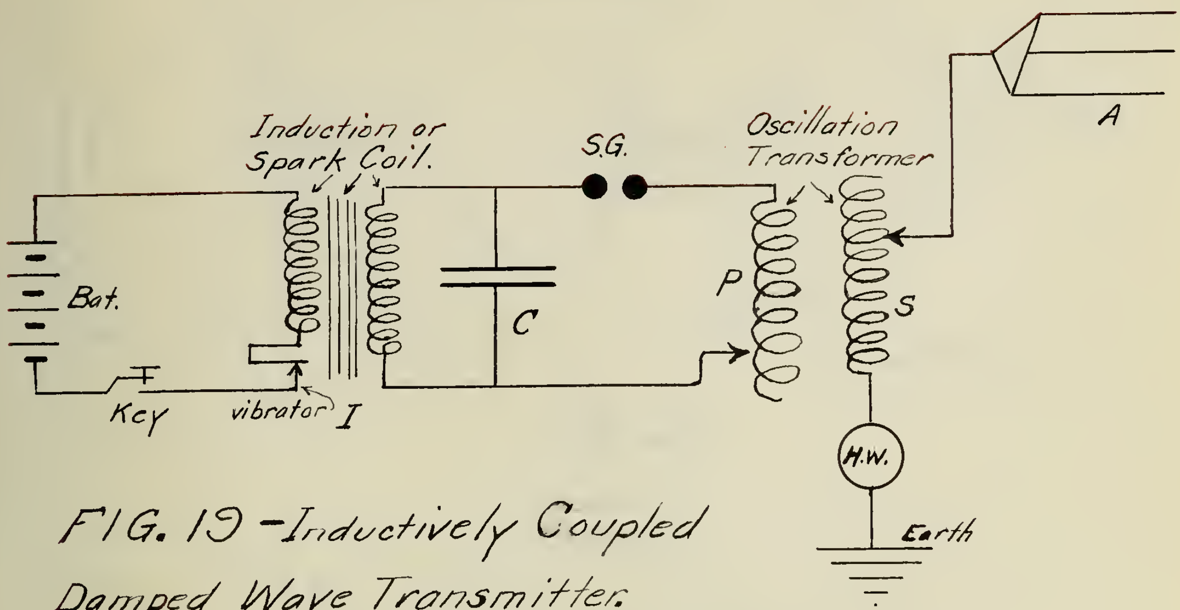


FIG. 19 – Inductively Coupled Damped Wave Transmitter.

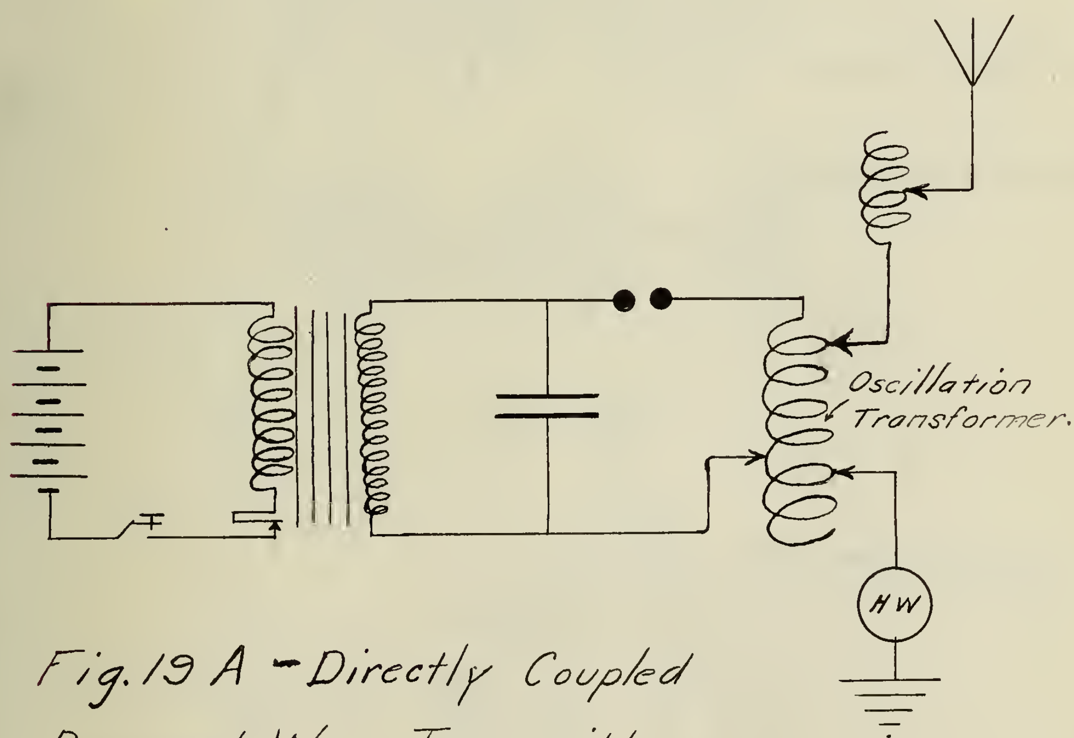


Fig. 19 A – Directly Coupled Damped Wave Transmitter

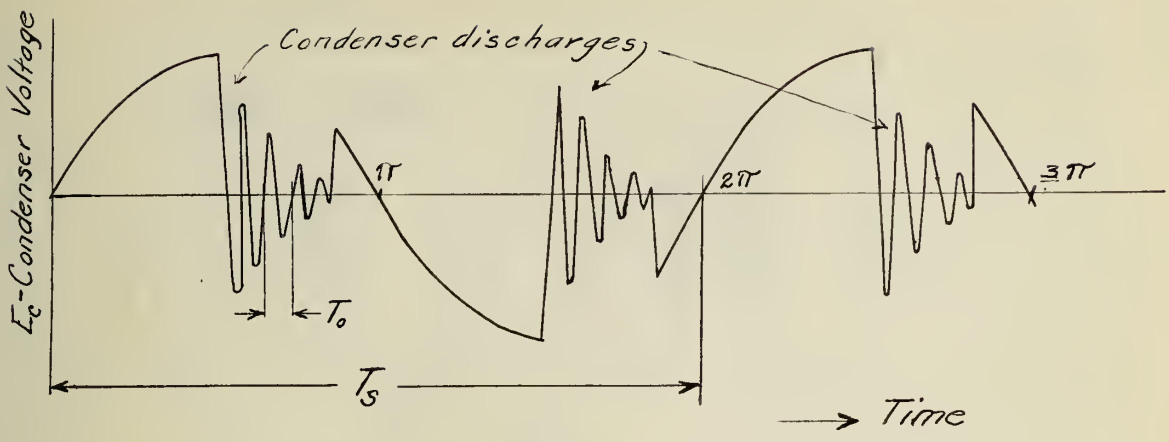


Fig. 20.

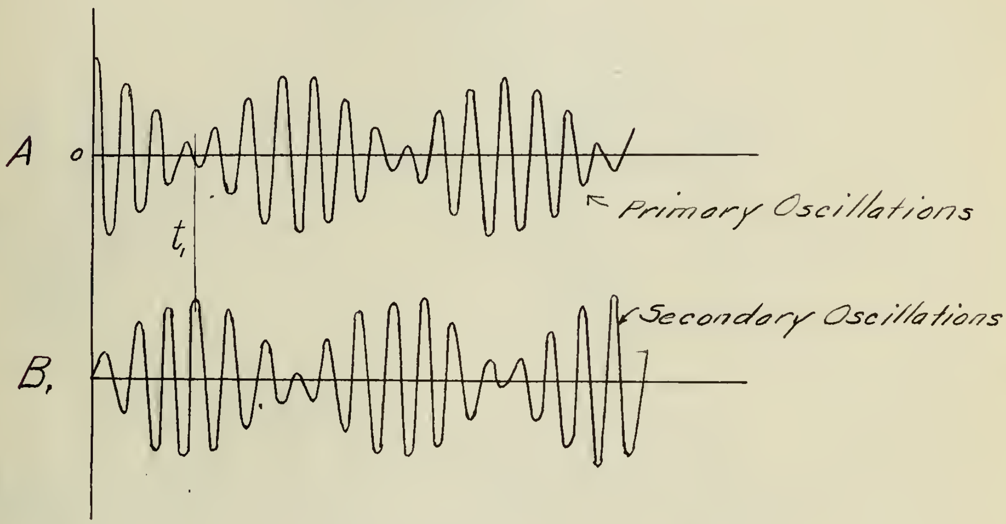


Fig. 21.

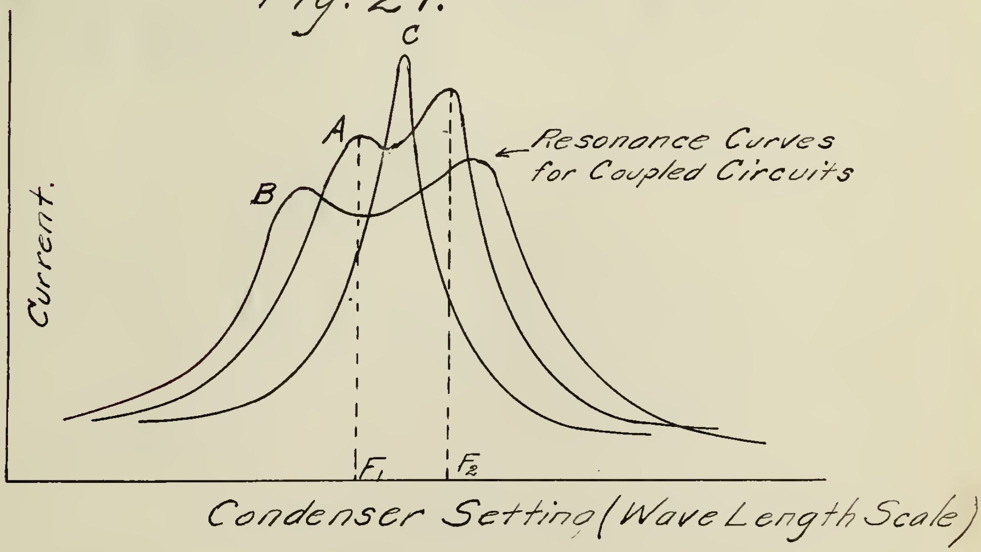


Fig. 22.

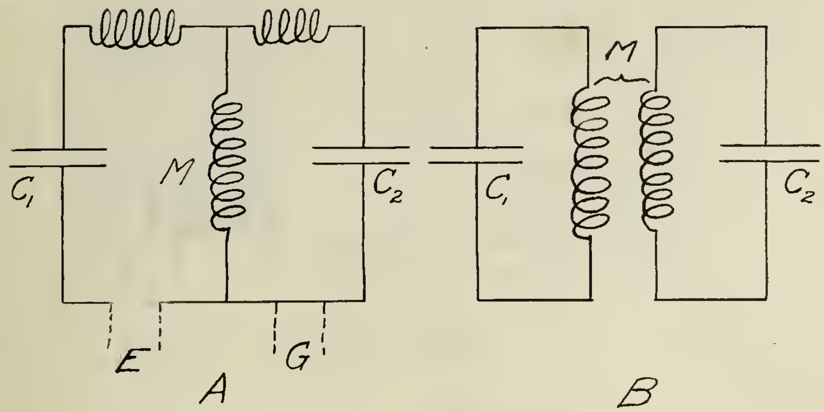


Fig. 23.

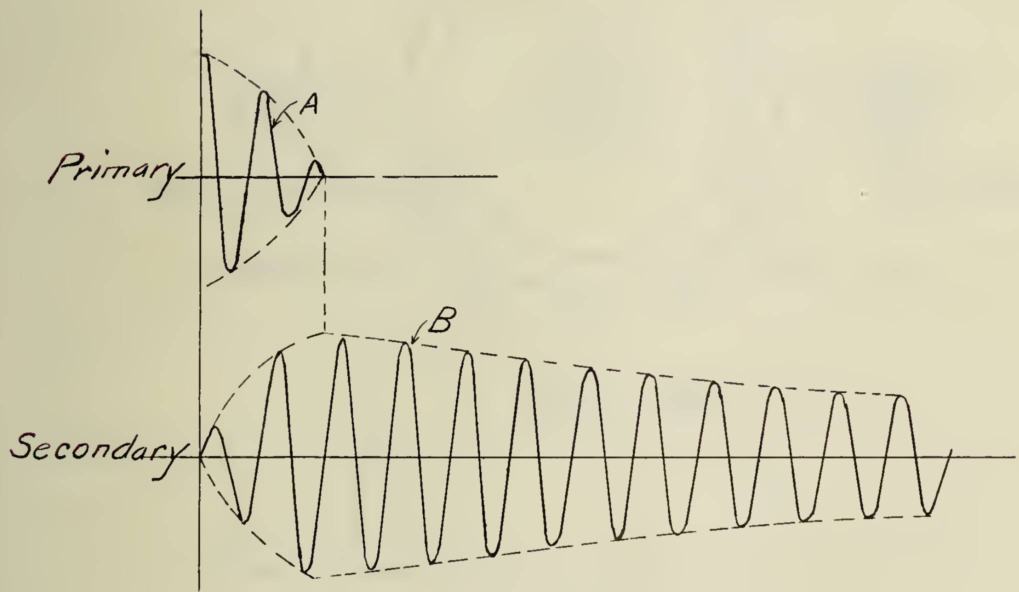


Fig. 24.

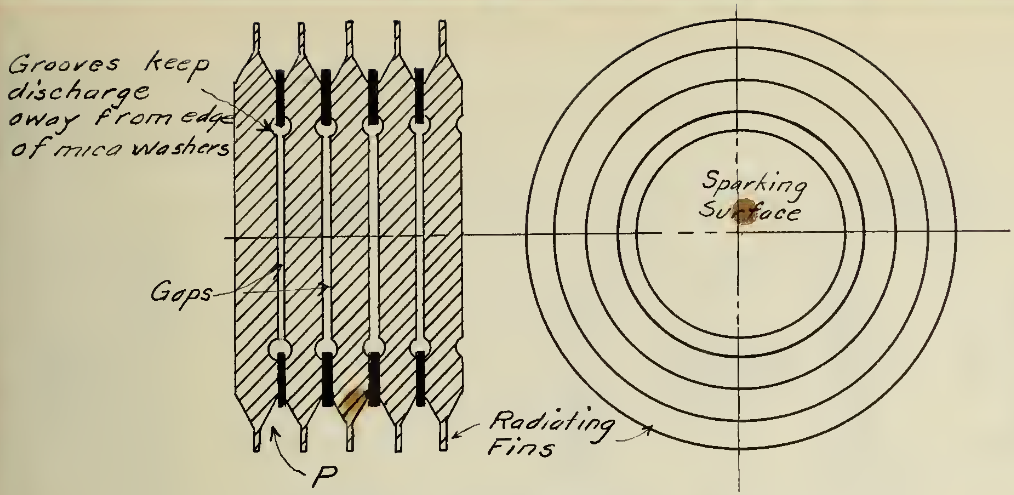


Fig. 25.

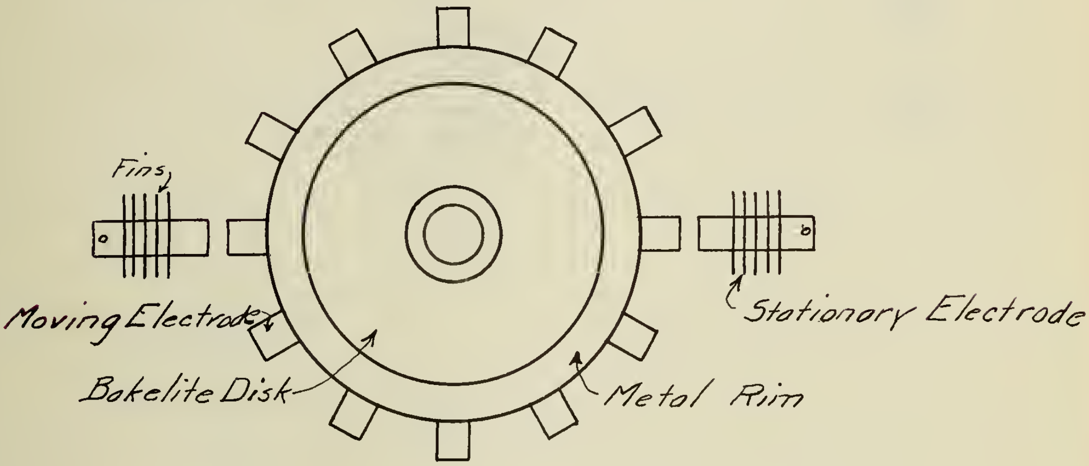


Fig. 26.

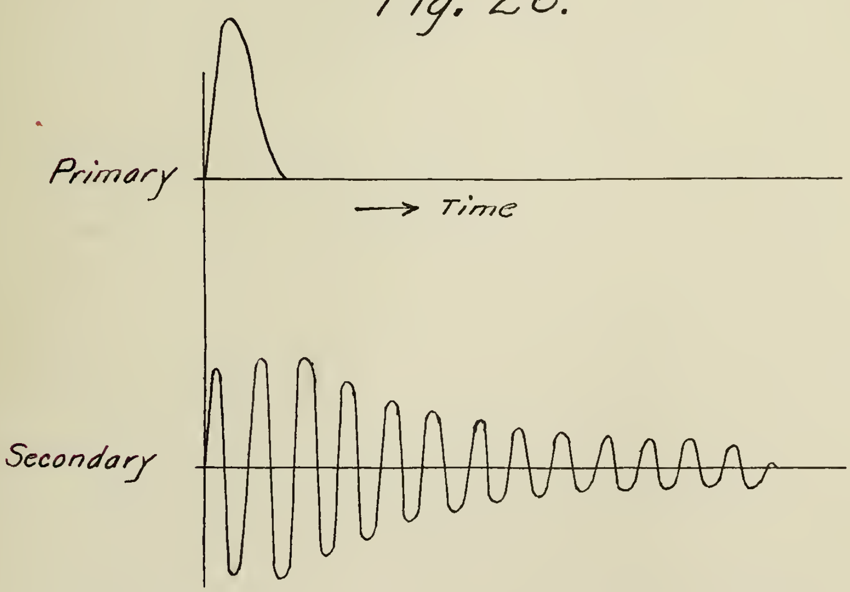


Fig. 27.

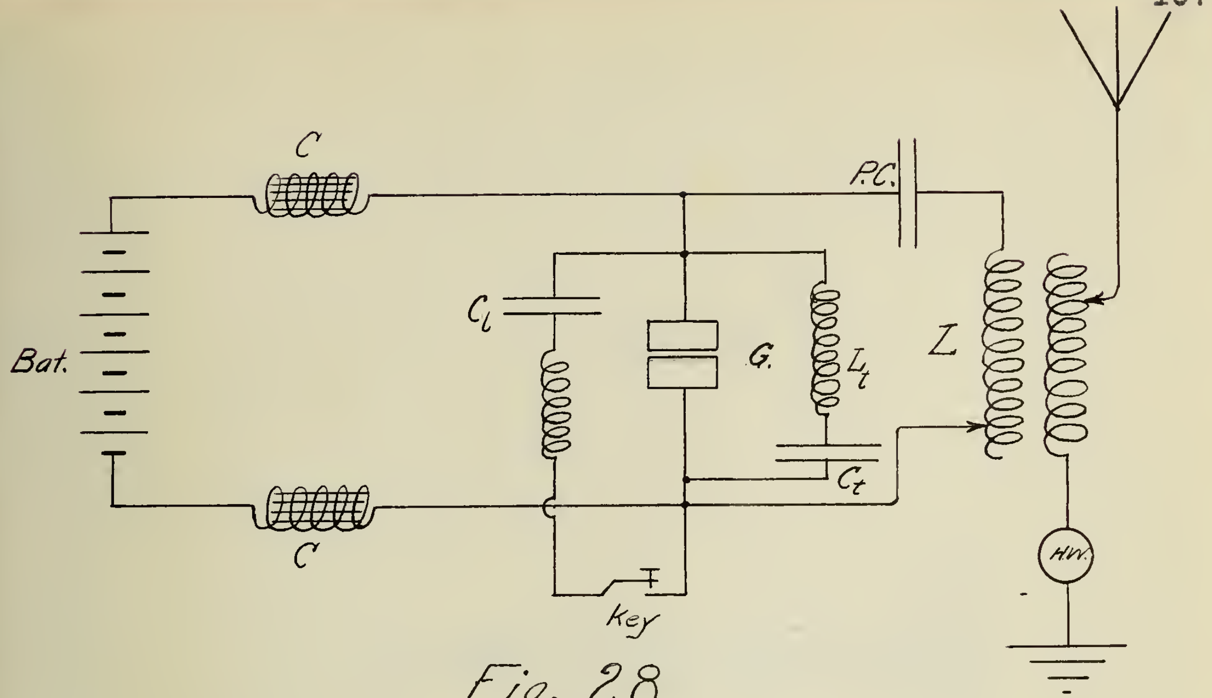


Fig. 28.

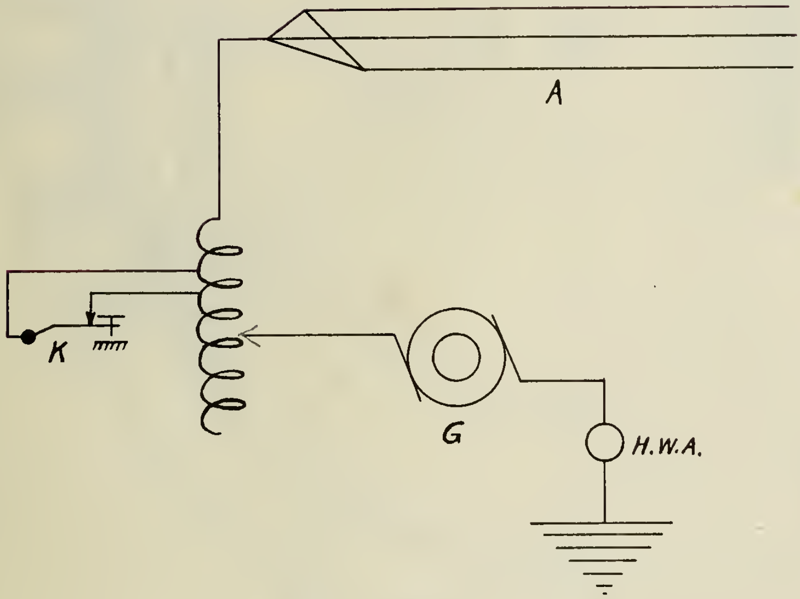


Fig. 29.

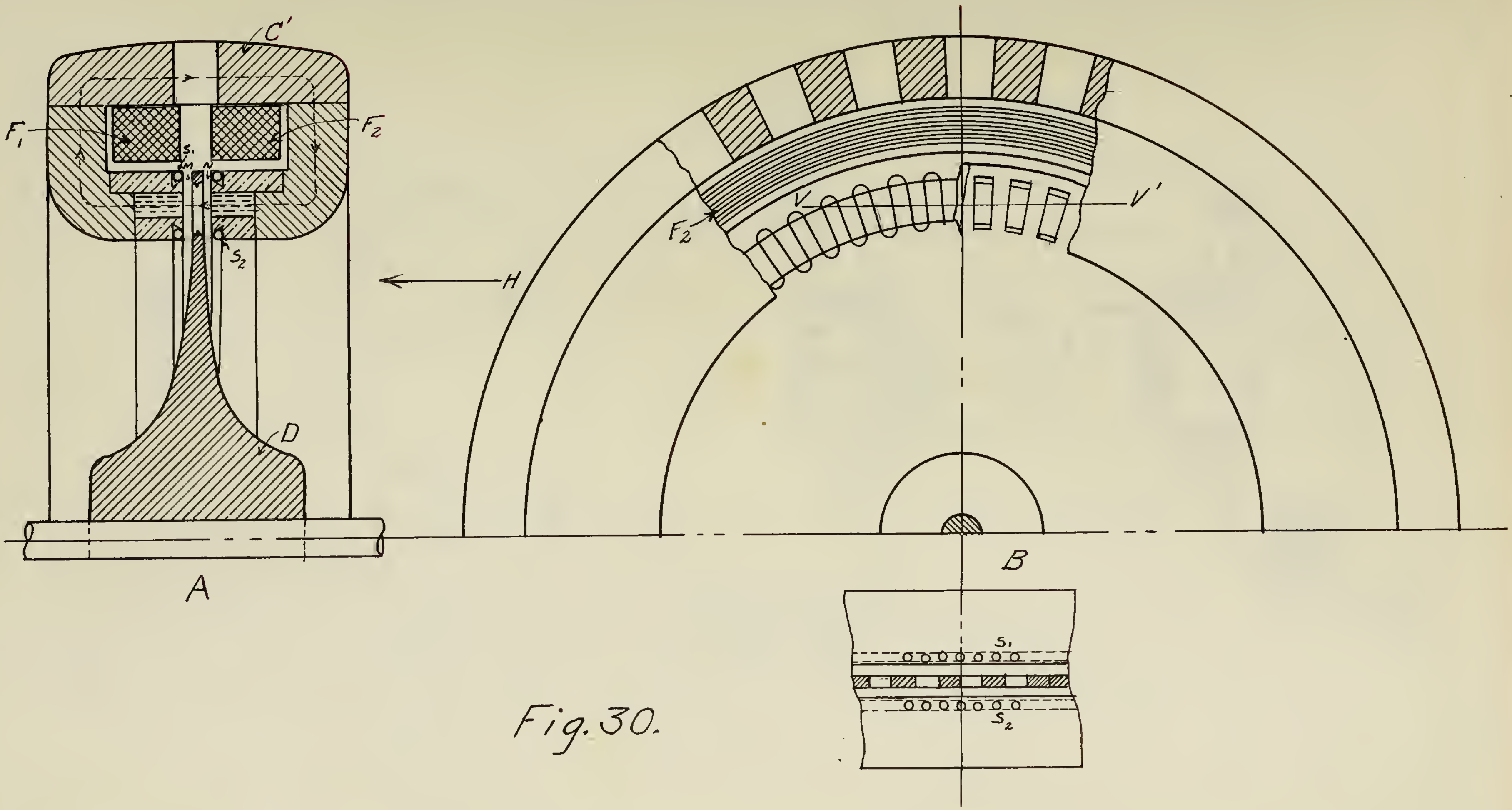


Fig. 30.

C - Plan Sectional View at V-V'

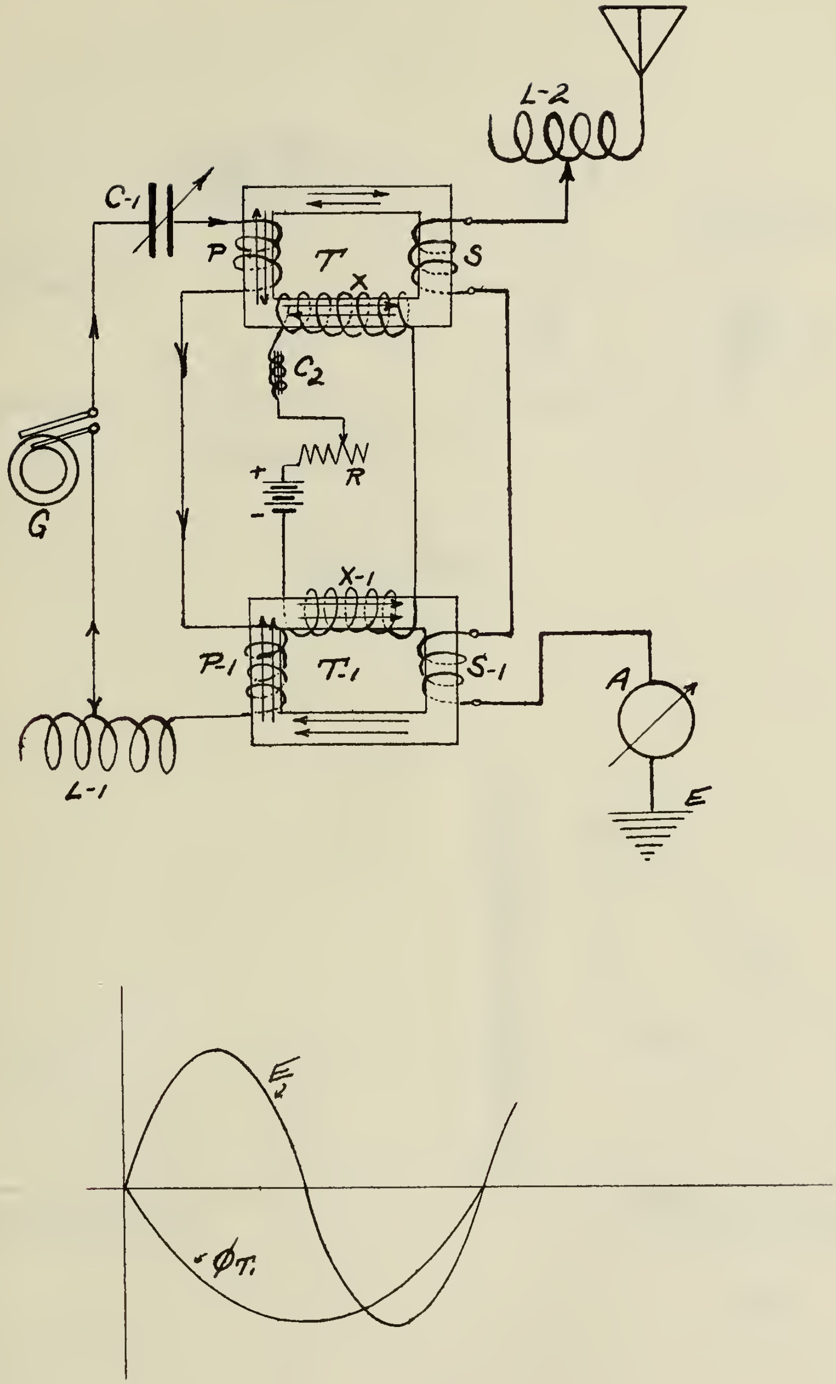


Fig. 31.

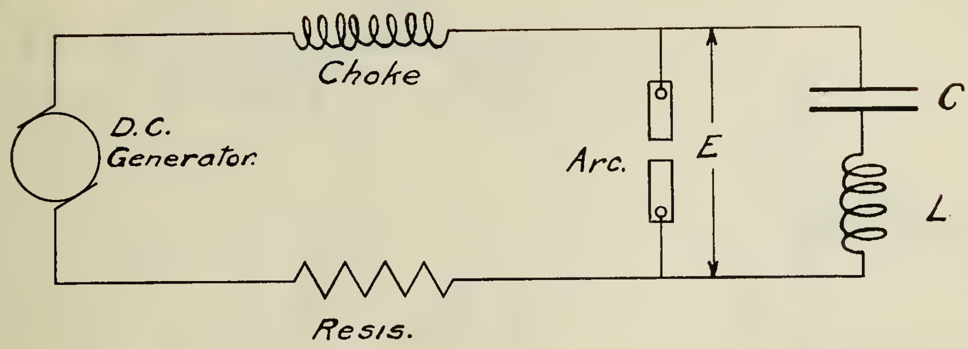

Choke
D.C.
Generator.
Arc.
E
C
L
Resis.

Fig. 32.

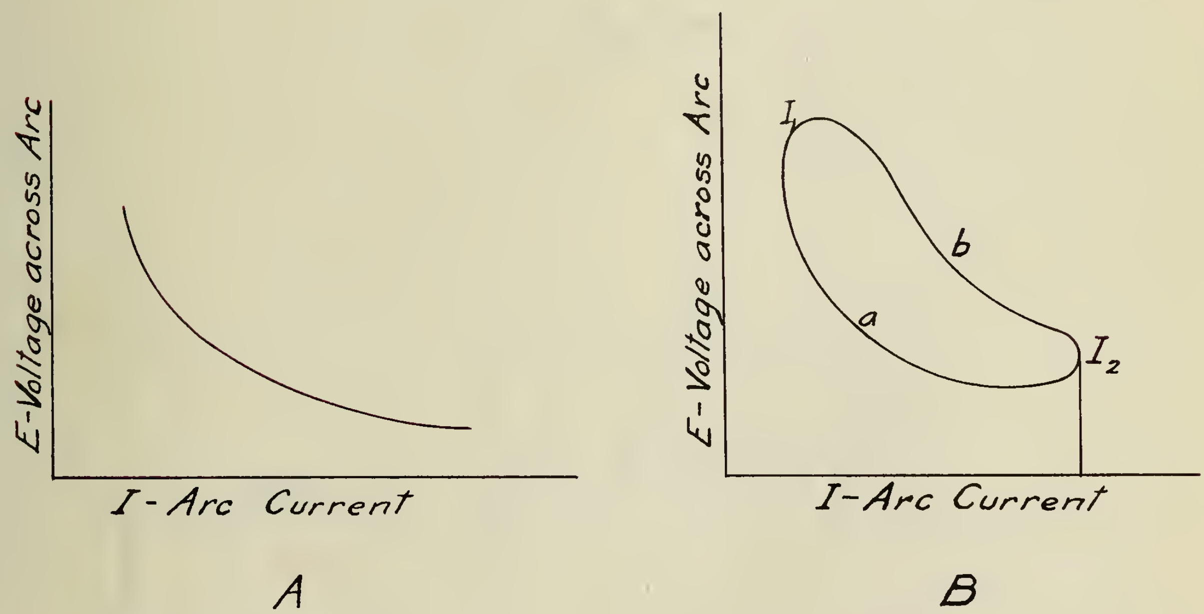

E-Voltage across Arc
I - Arc Current
A
E-Voltage across Arc
I_1
b
a
I_2
I-Arc Current
B

Fig. 33.

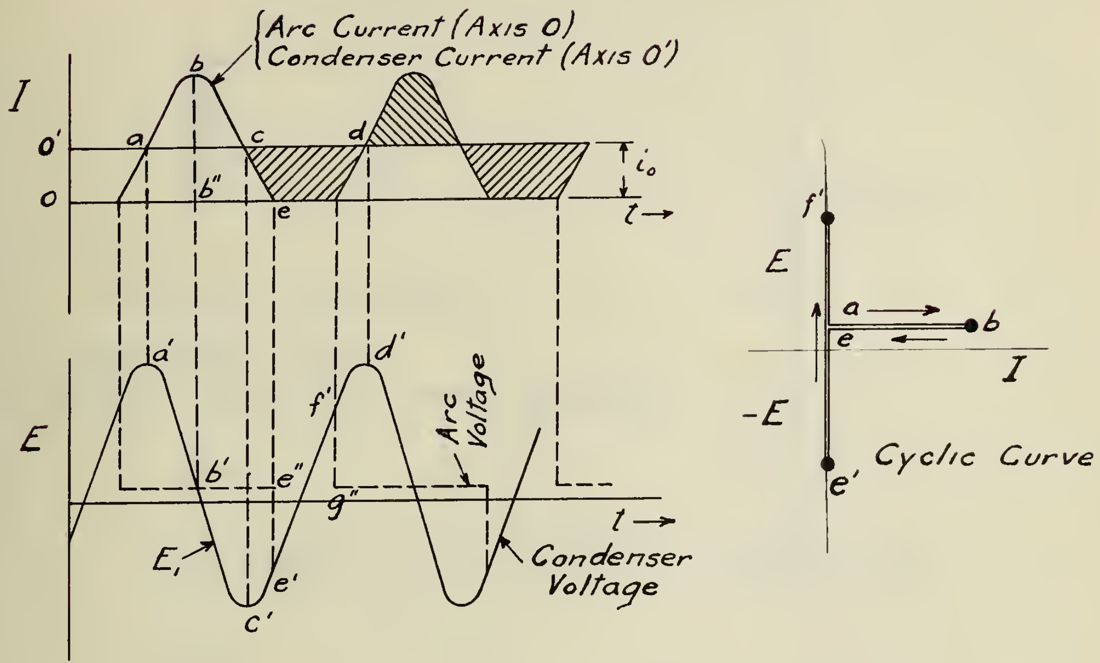

Arc Current (Axis O)
Condenser Current (Axis O')
I
b
a
c
d
O'
O
b''
e
i_o
t →
f'
E
a
b
e
I
-E
e'
Cyclic Curve
a'
d'
f''
Arc Voltage
E
b'
e''
g''
t →
E_1
e'
c'
Condenser Voltage

Fig. 34.

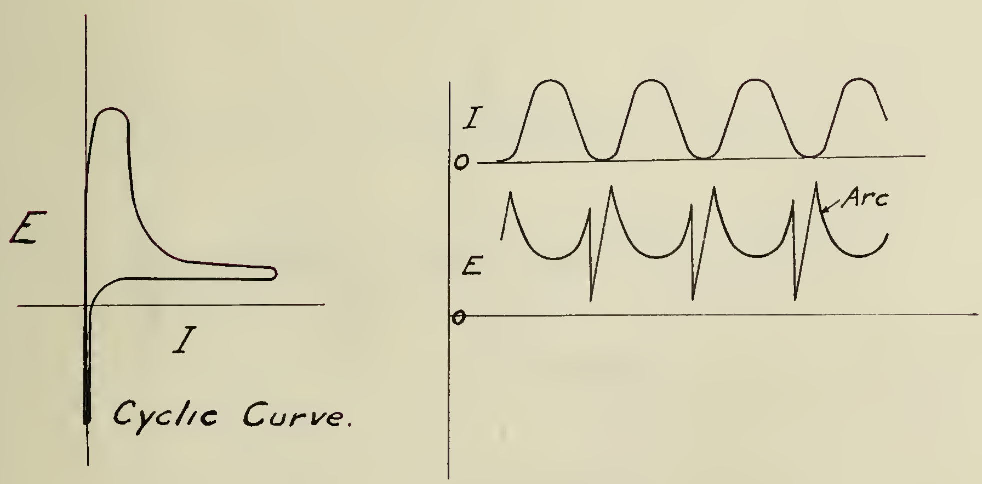

E
I
Cyclic Curve.
I
O
Arc
E
O

Fig. 35.

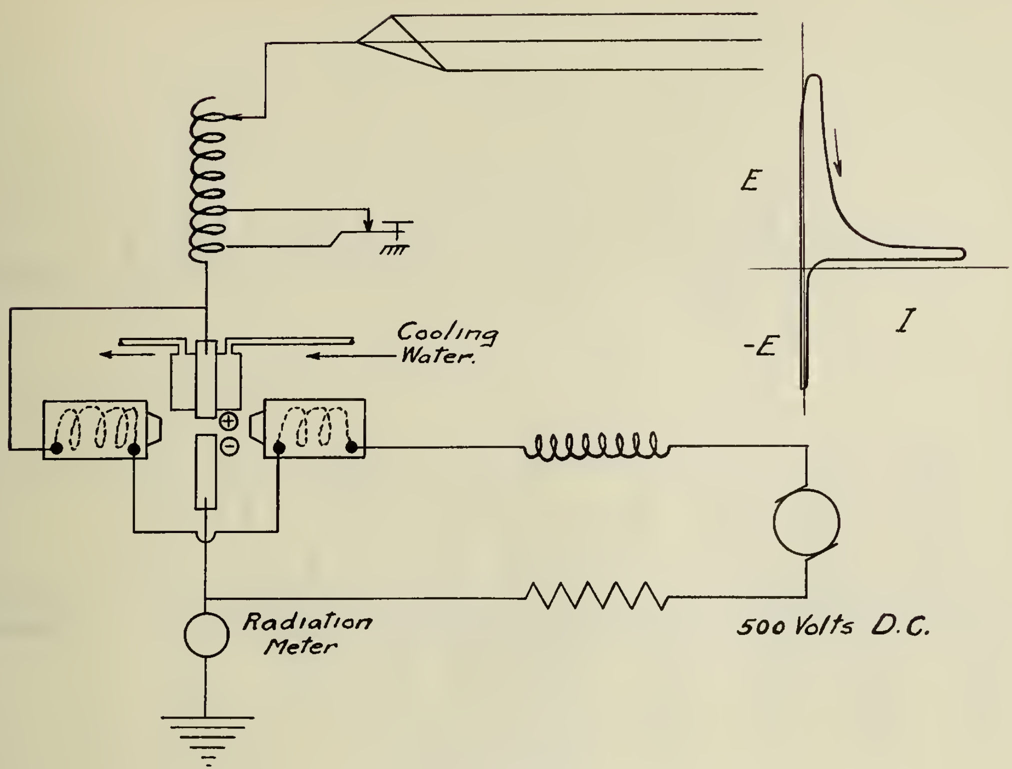

E
-E
I
Cooling
Water.
Radiation
Meter
500 Volts D.C.

Fig. 36.

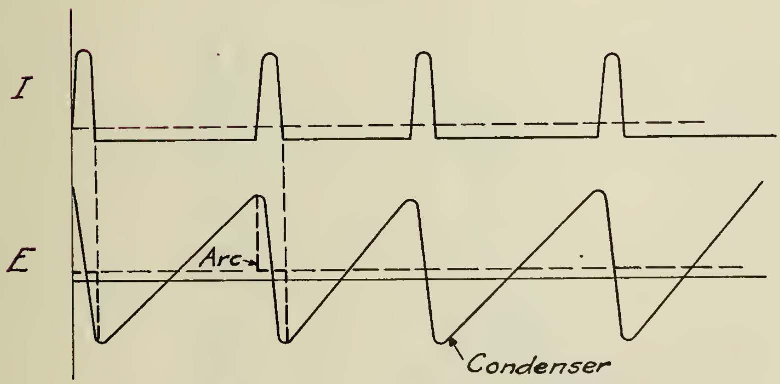

I
E
Arc
Condenser

Fig. 37.

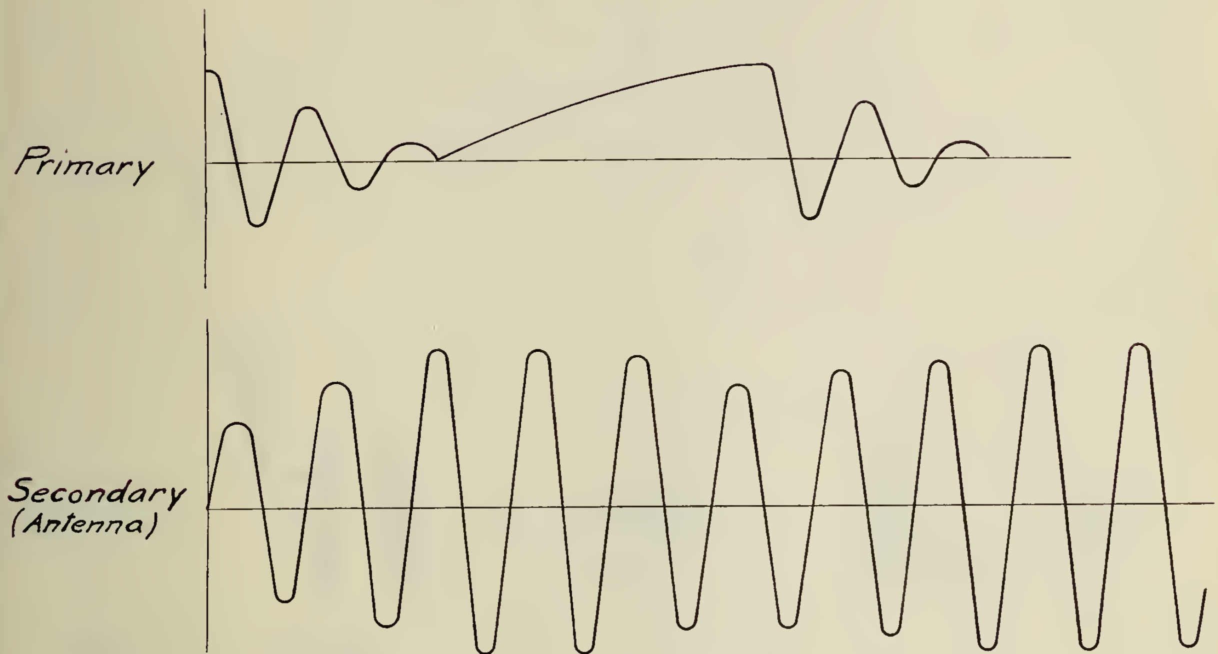

Primary
Secondary
(Antenna)

Fig. 38.

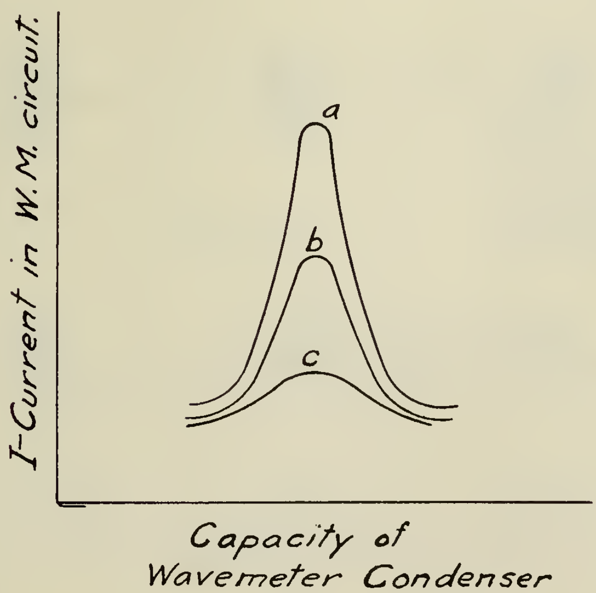

I-Current in W. M. circuit.
a
b
c
Capacity of
Wavemeter Condenser

Fig. 39.

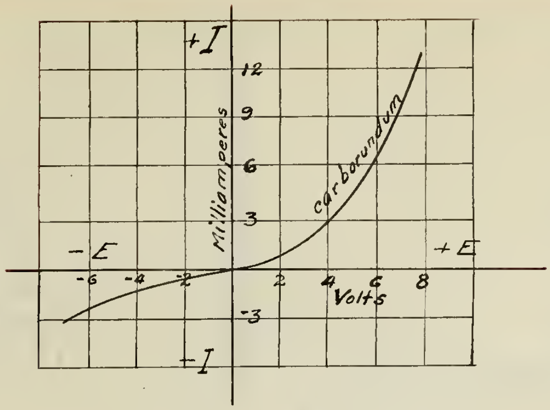


Fig. 40.

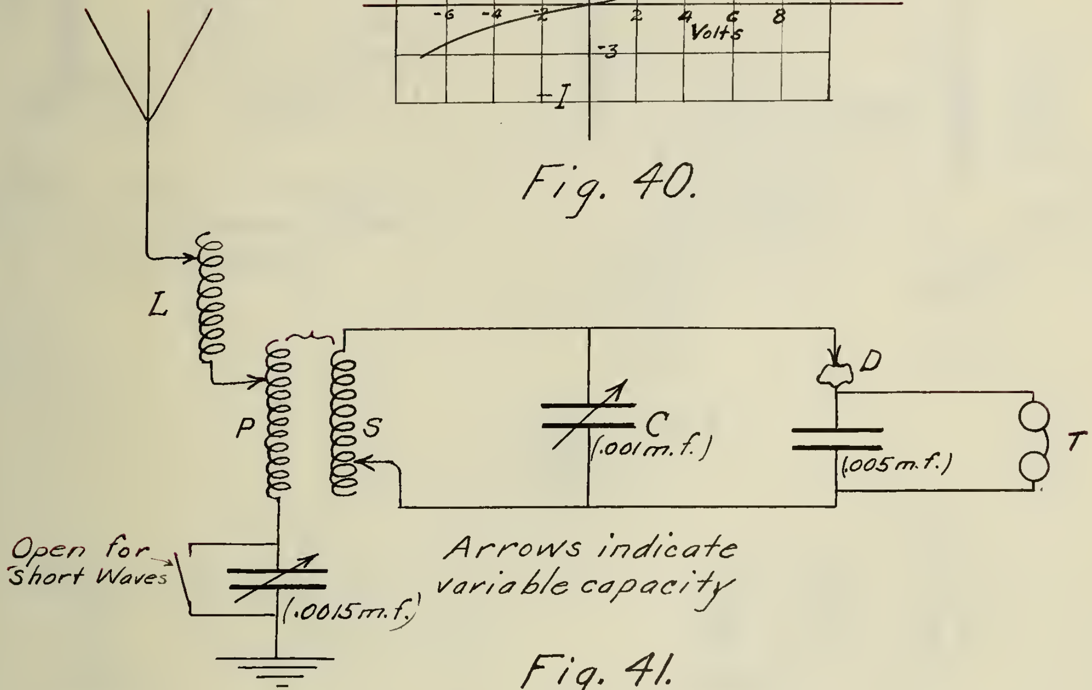


Fig. 41.

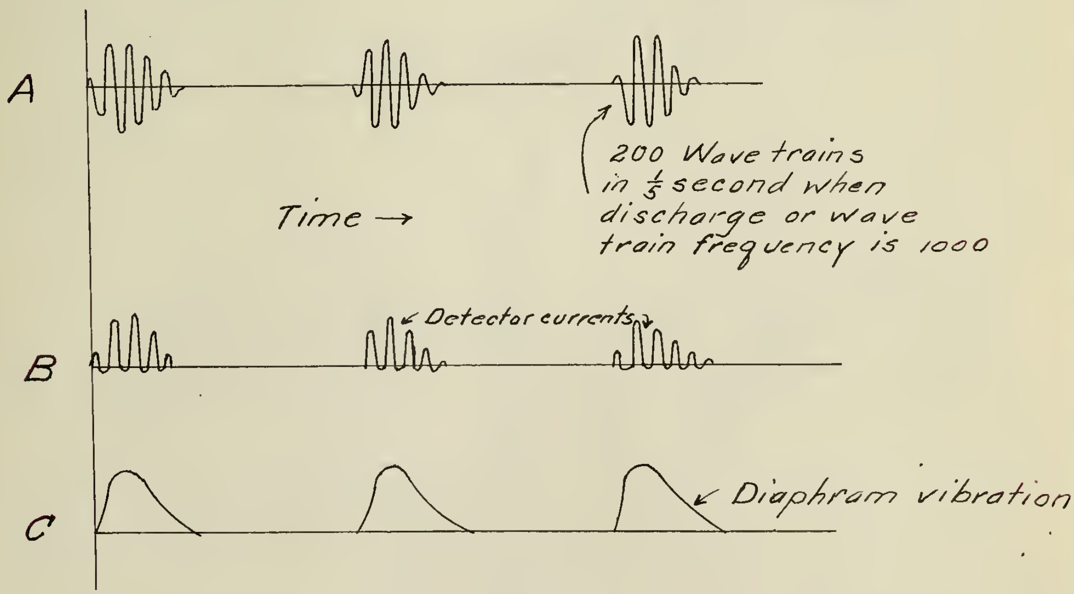


Fig. 42.

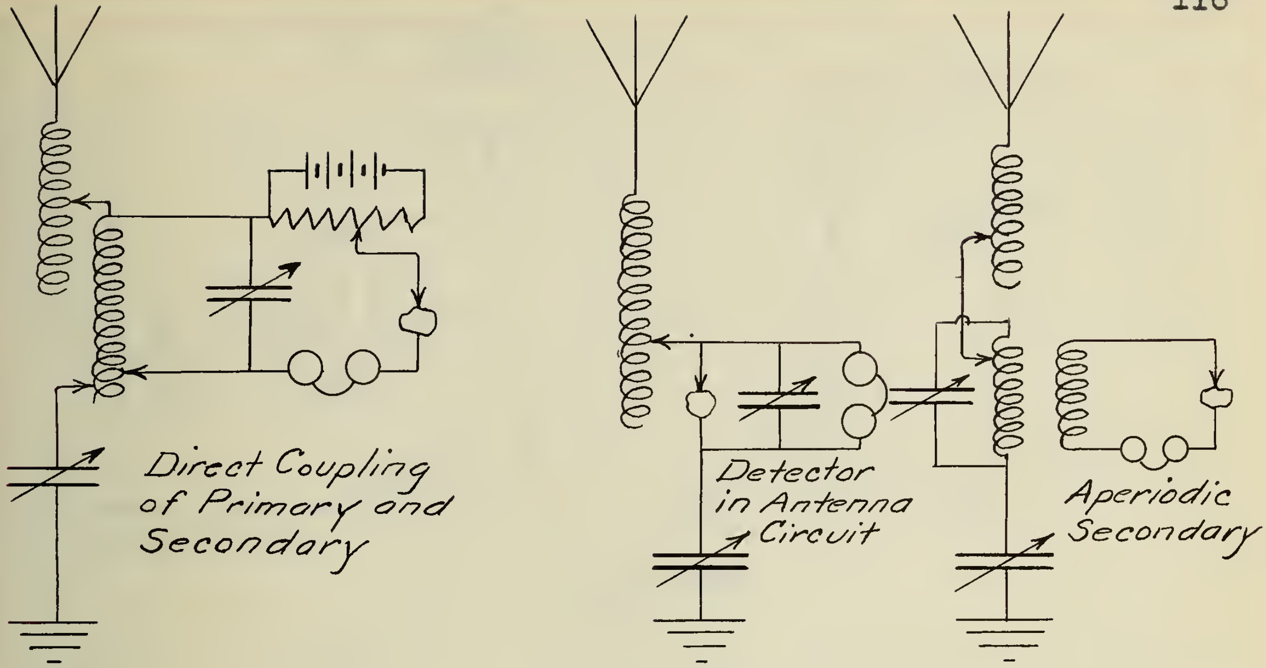


Fig. 43.

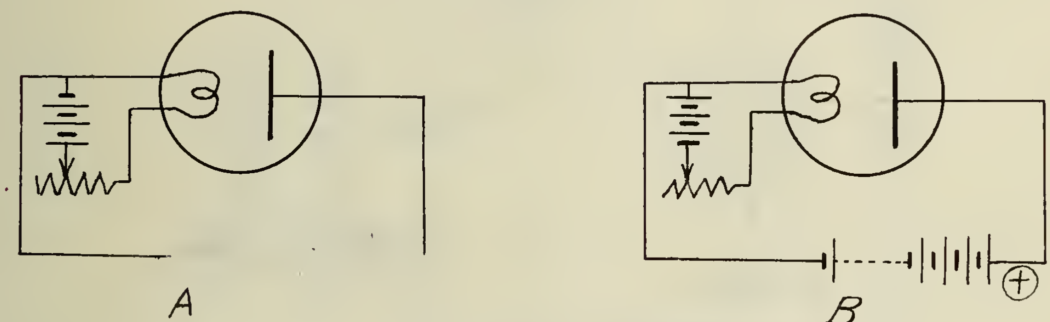


Fig. 44.

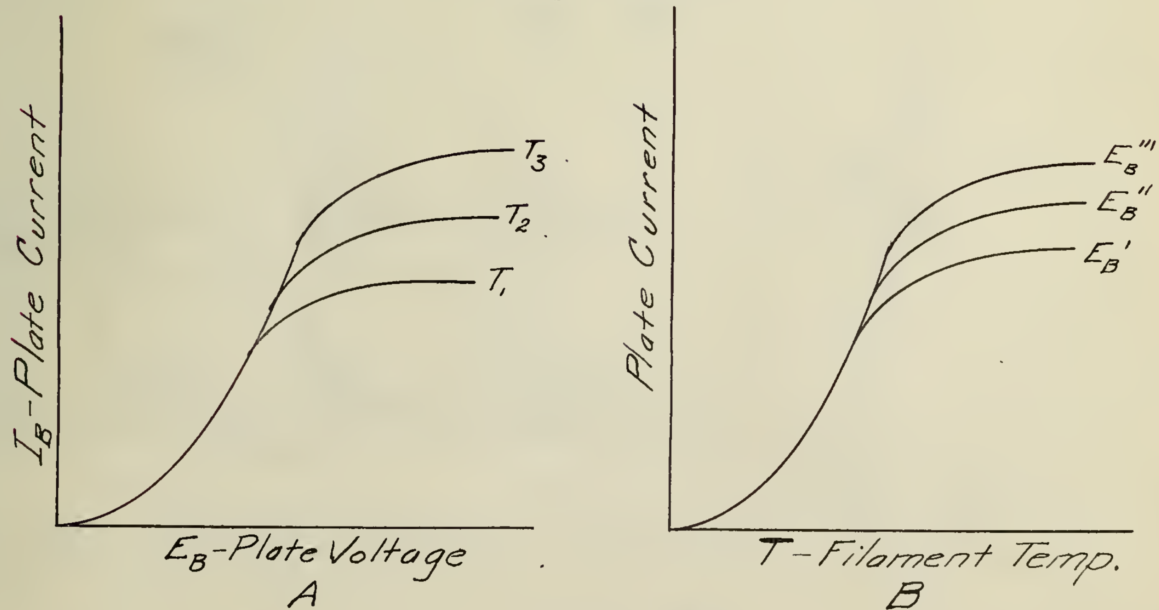


Fig. 45.

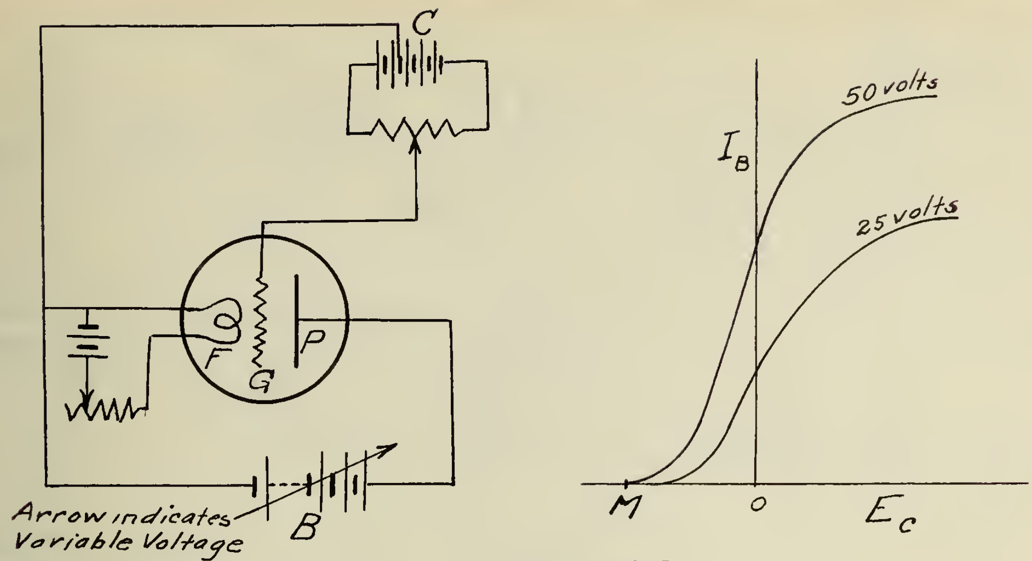


Fig. 46.

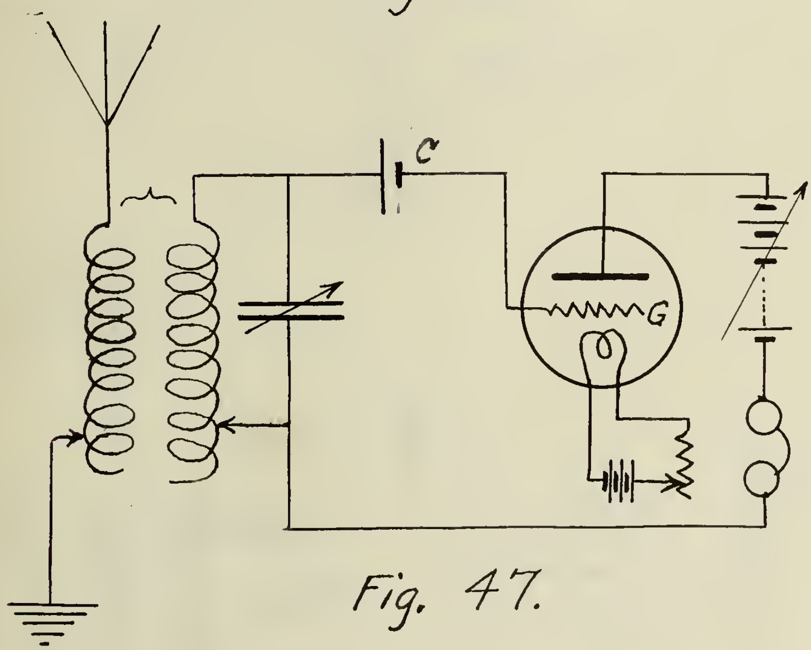


Fig. 47.

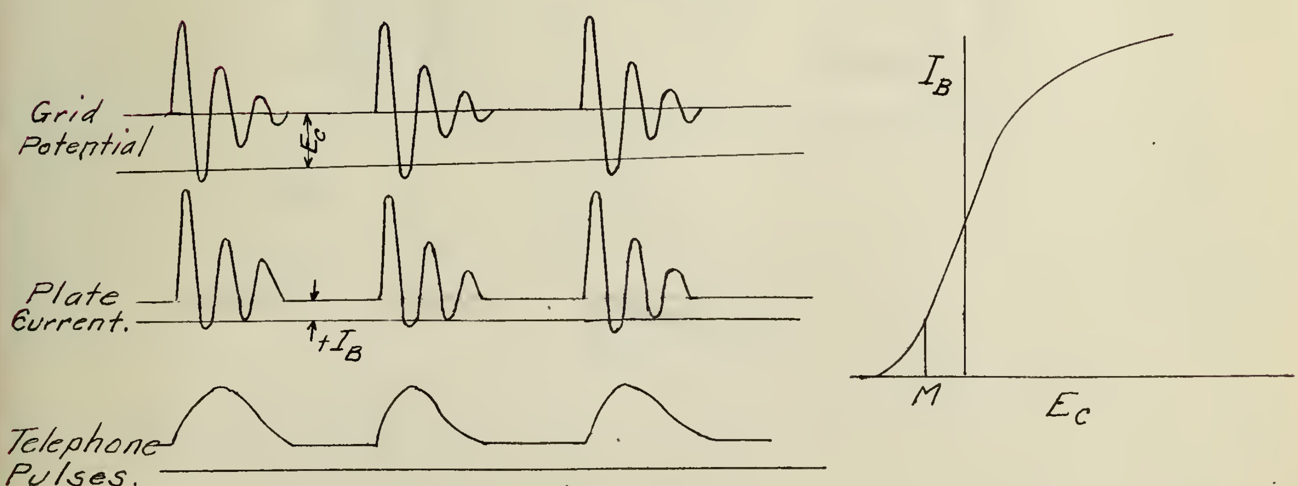


Fig. 48.

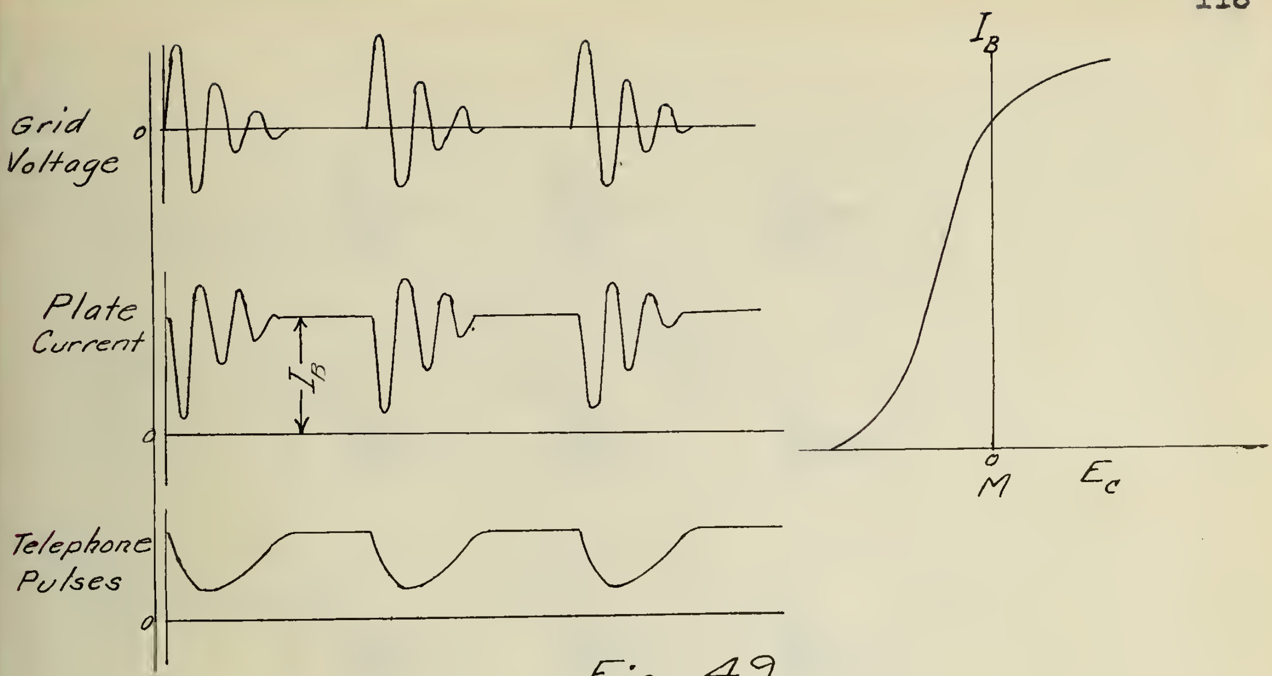


Fig. 49.

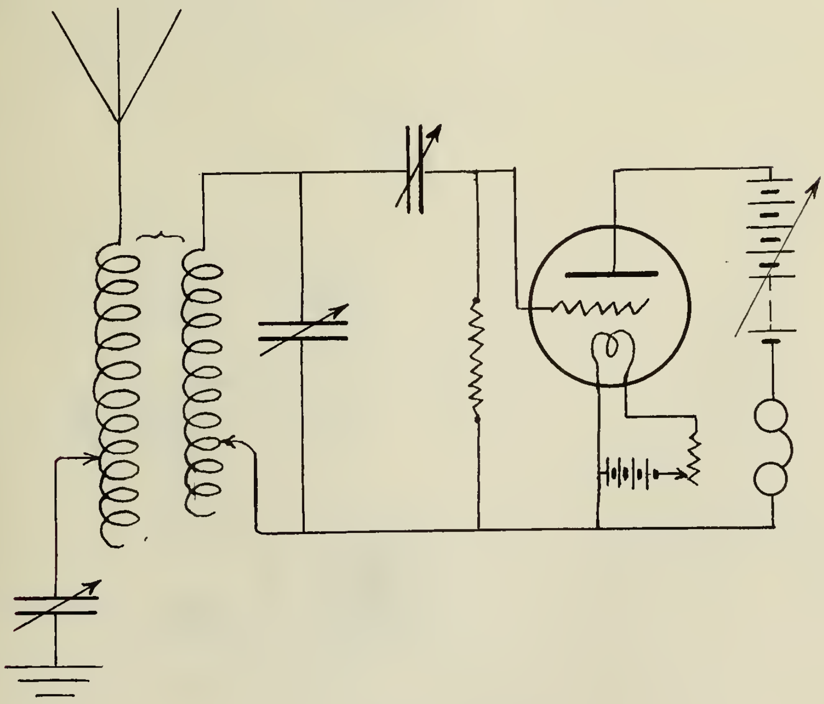


Fig. 50.

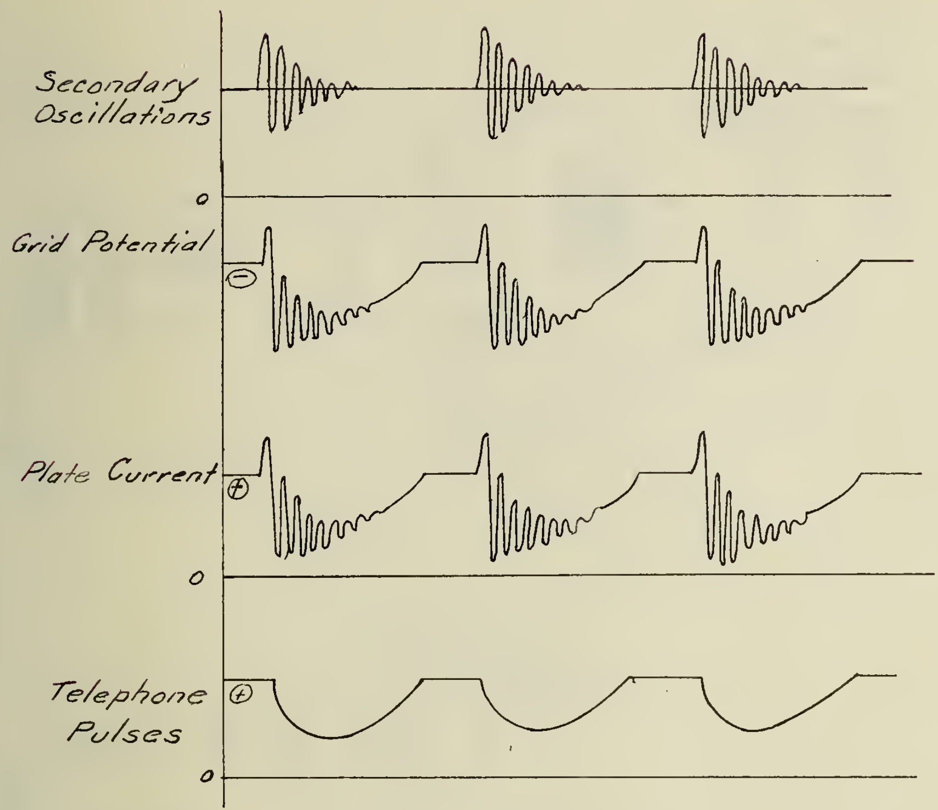
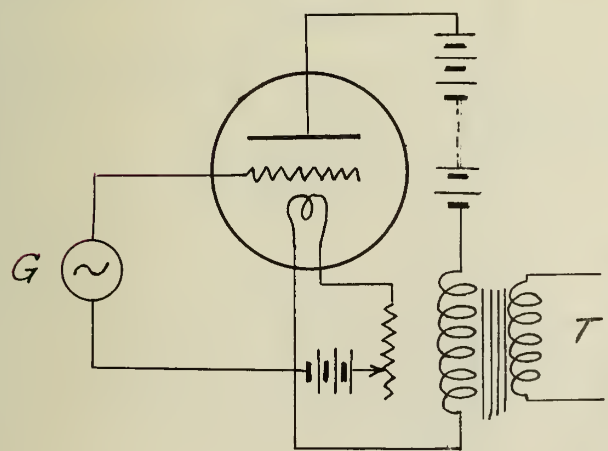


Fig. 51.



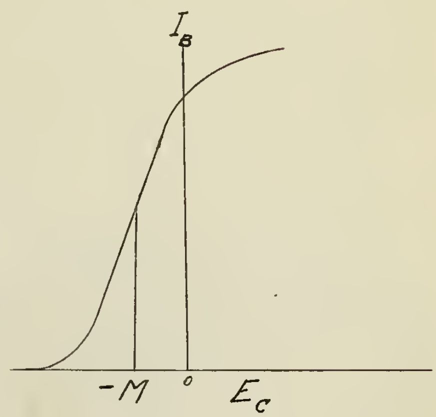


Fig. 53

Fig. 52

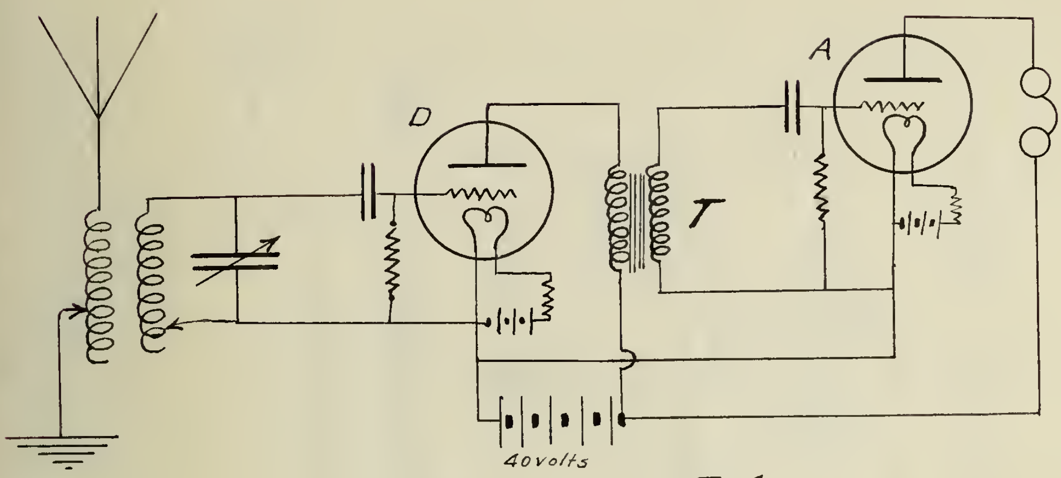


Fig. 54.

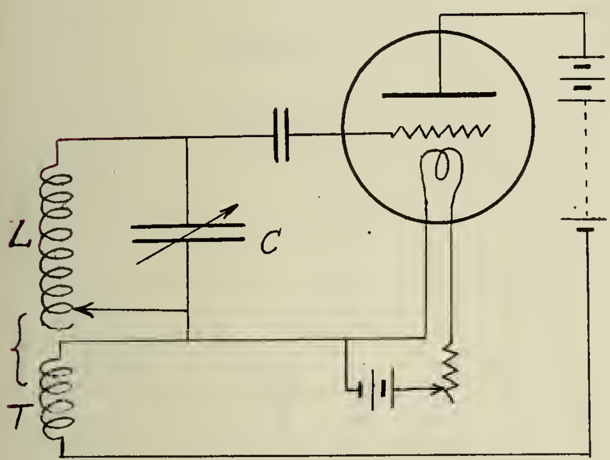


Fig. 55.

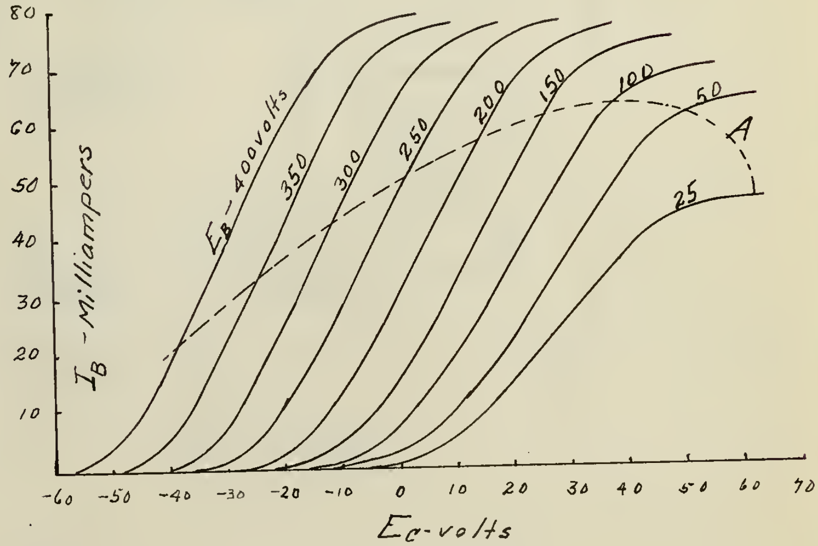


Fig. 56.

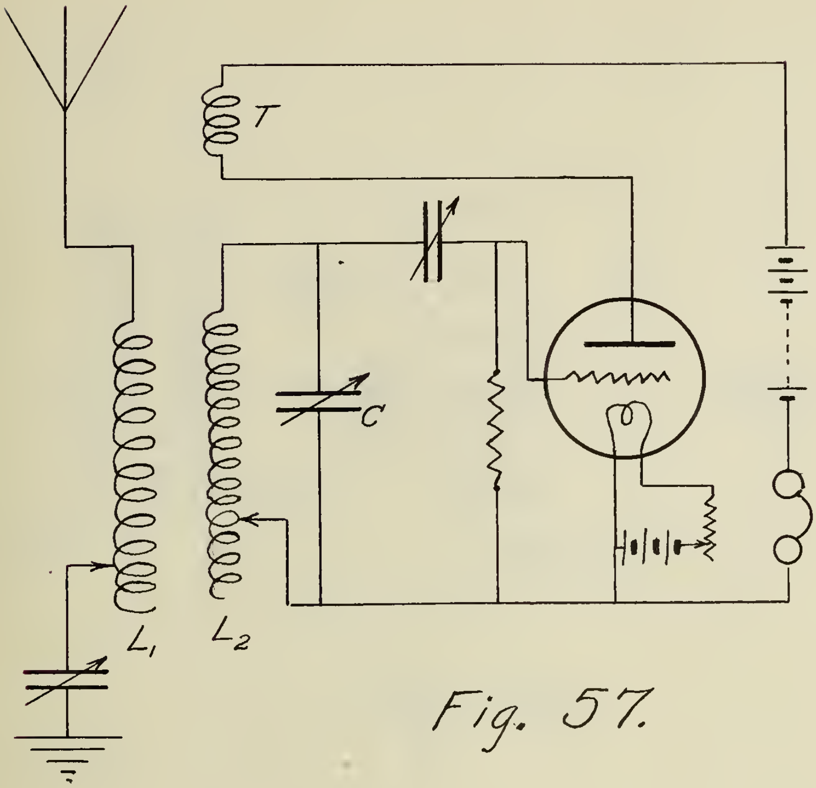

T
C
L1
L2

Fig. 57.

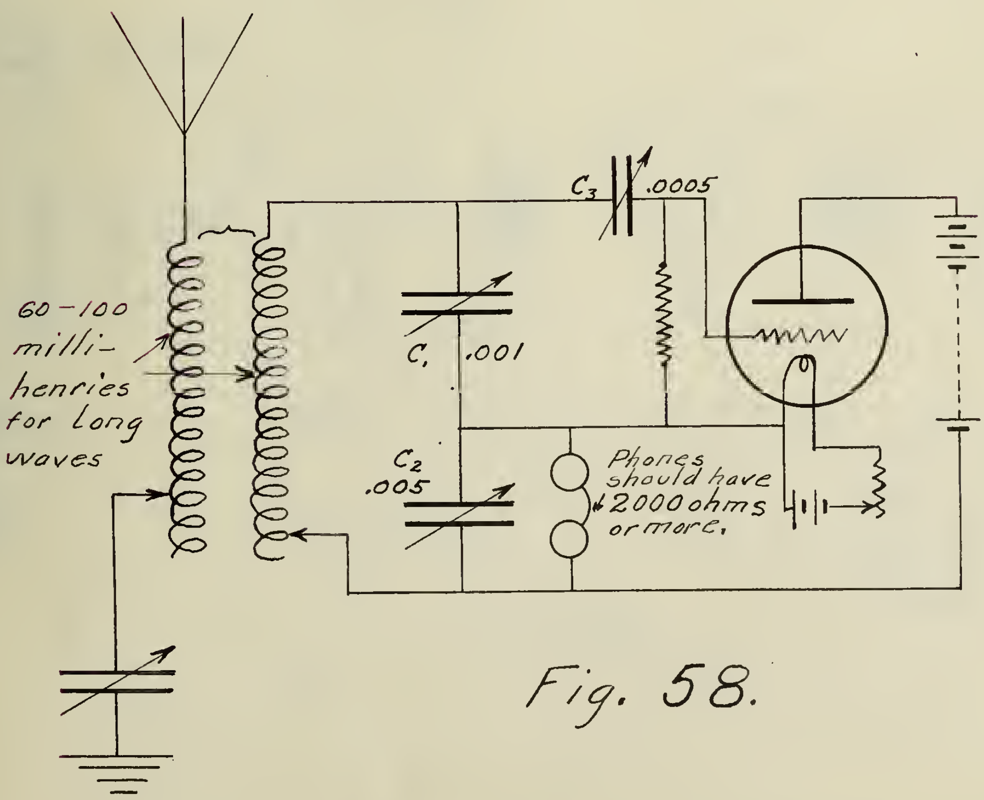

C3
.0005
60-100
milli-
henries
for long
waves
C1
.001
C2
.005
Phones
should have
2000 ohms
or more.

Fig. 58.

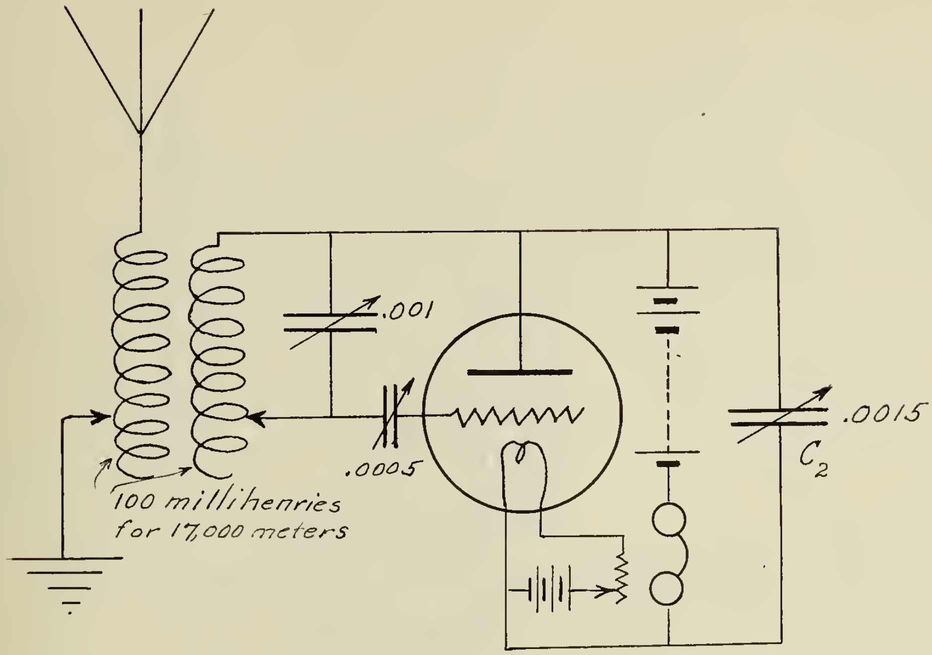
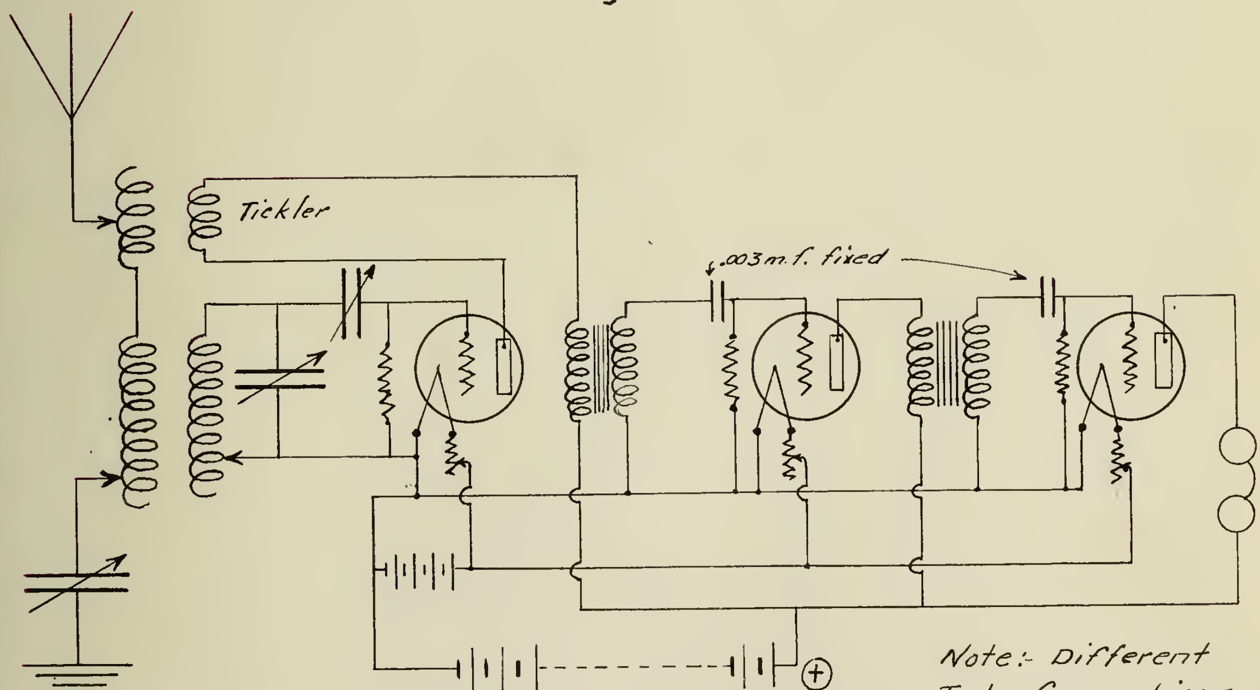


Fig. 59.



Note:- Different Tube Conventions used in order to simplify diagram.

Fig. 60.

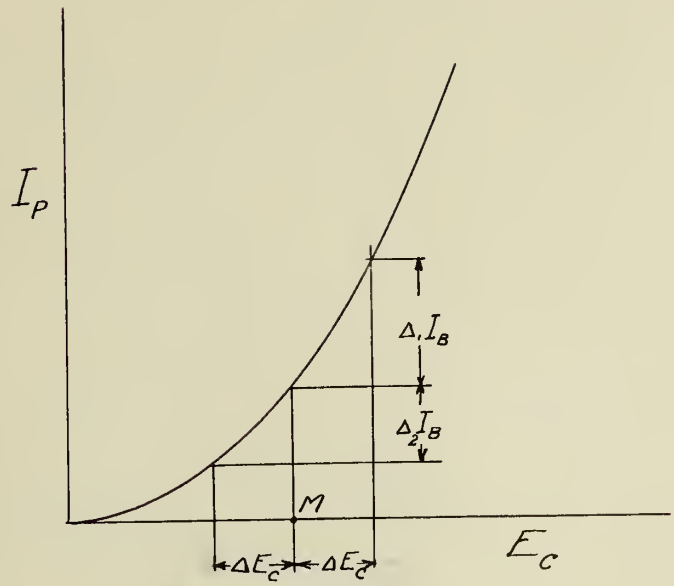


Fig. 61.

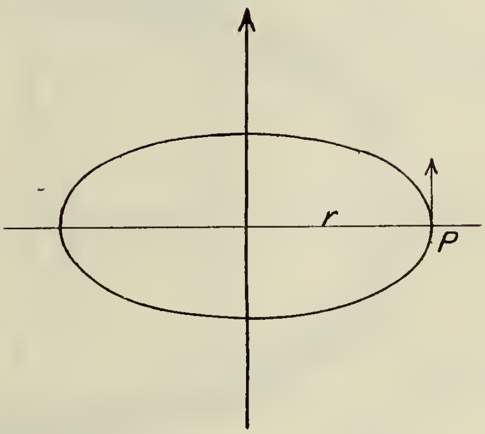
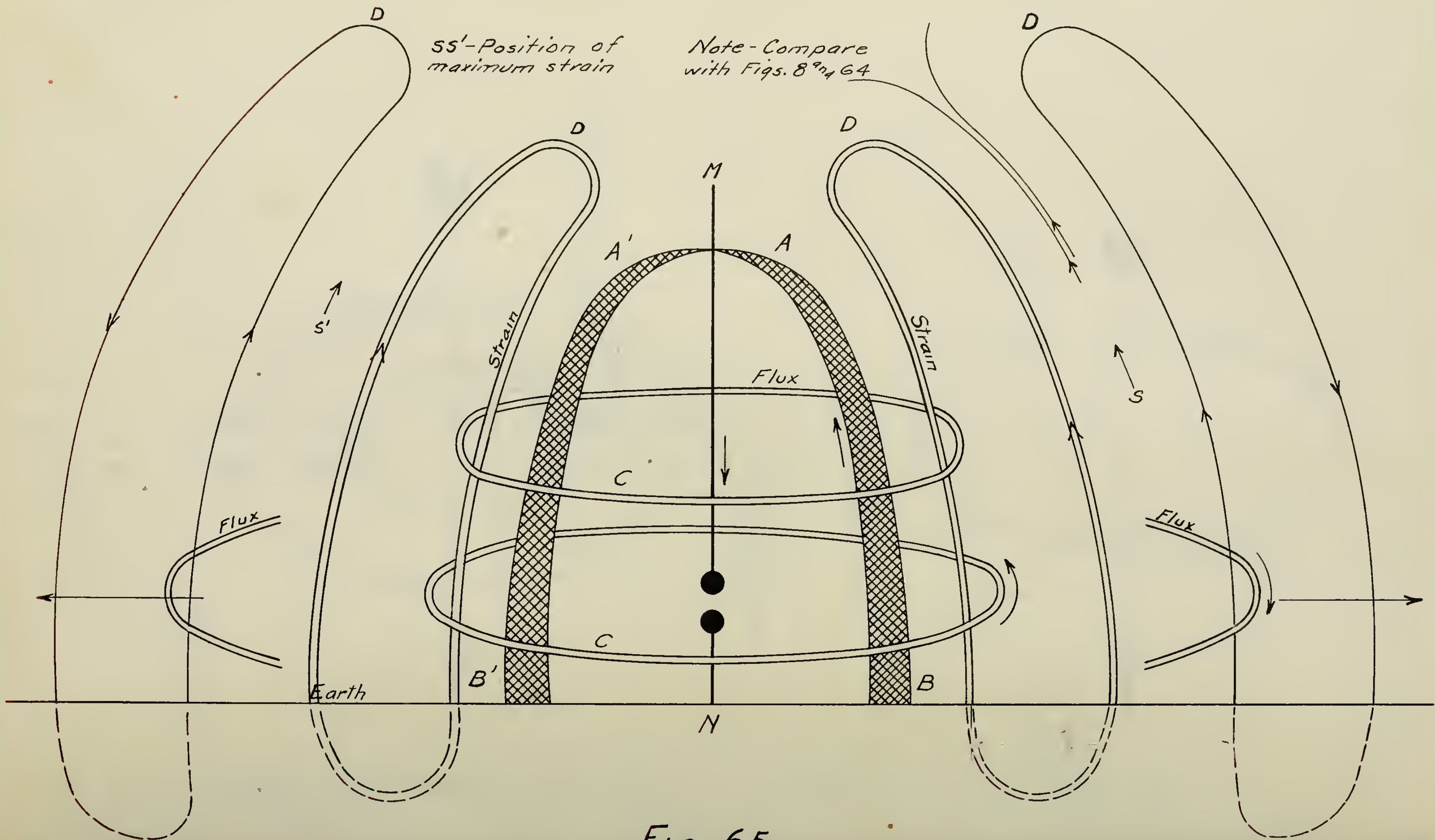


Fig. 62.



D
SS'-Position of maximum strain
Note-Compare with Figs. 8 and 64
D
D
D
M
A'
A
S'
Strain
Strain
S
Flux
C
Flux
Flux
C
Earth
B'
B
N

Fig. 65.

12

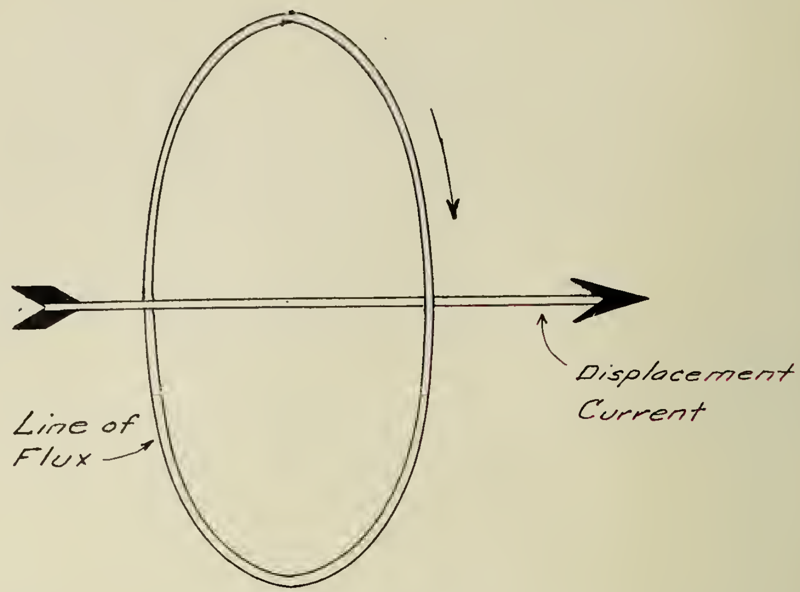

Displacement Current
Line of Flux

Fig. 63.

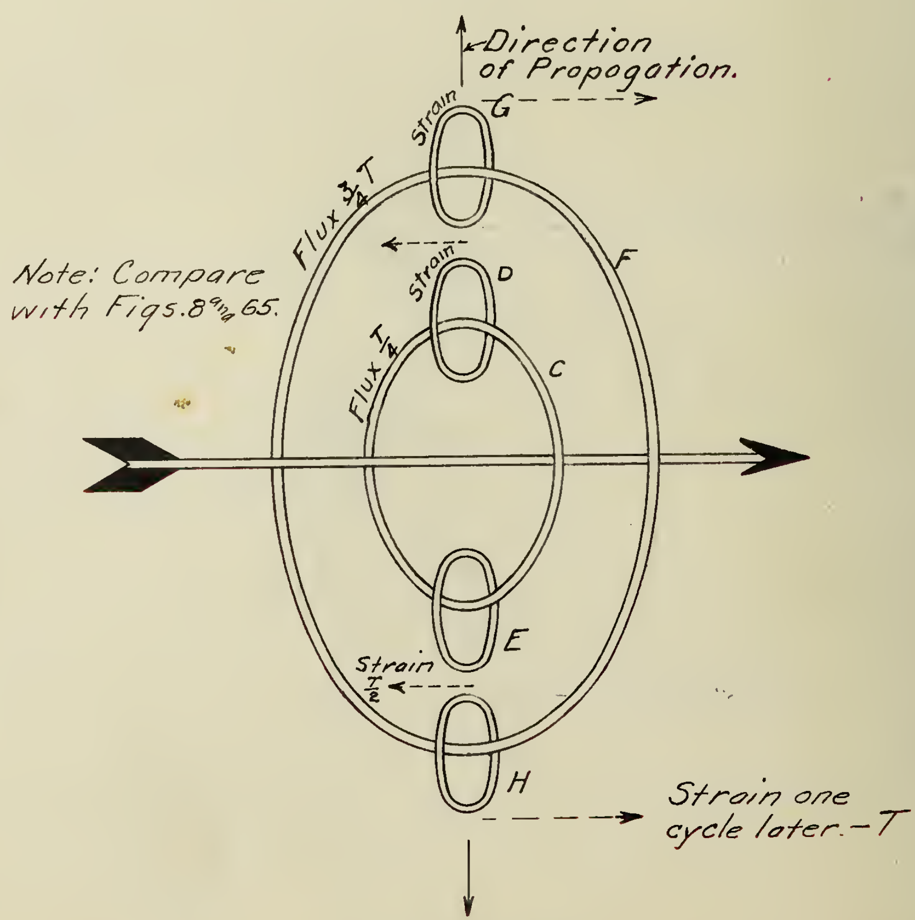

Direction of Propogation.
Strain
G
Flux $\frac{3}{4}T$
Note: Compare with Figs. 8 and 65.
Strain
D
F
Flux $\frac{T}{4}$
C
E
Strain $\frac{T}{2}$
H
Strain one cycle later.–T

Fig. 64.

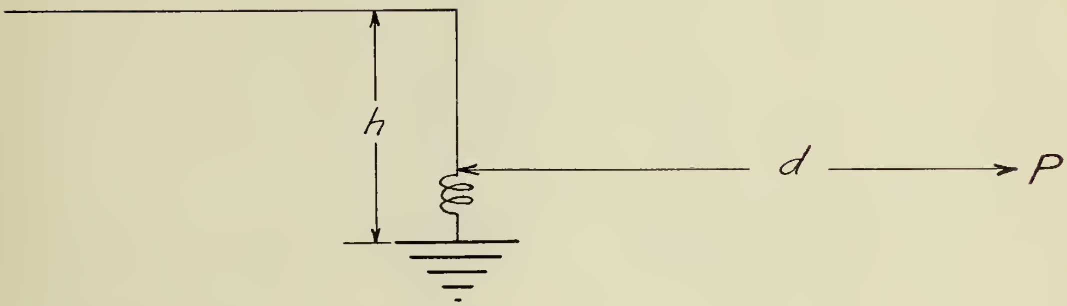


Fig. 66.

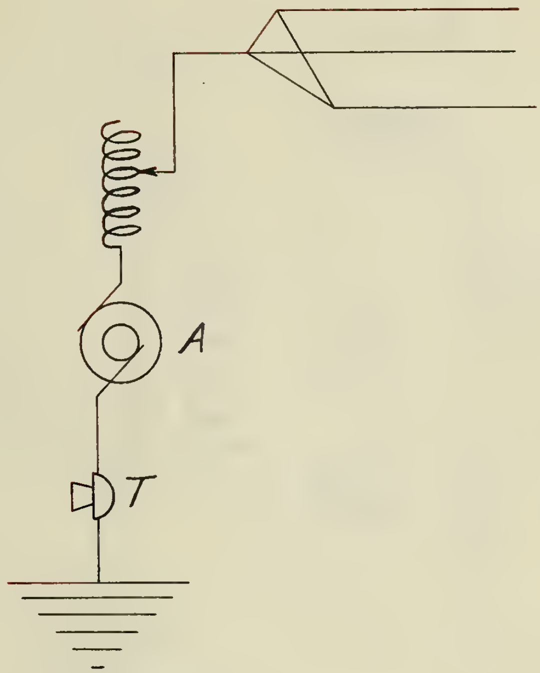


Fig. 67

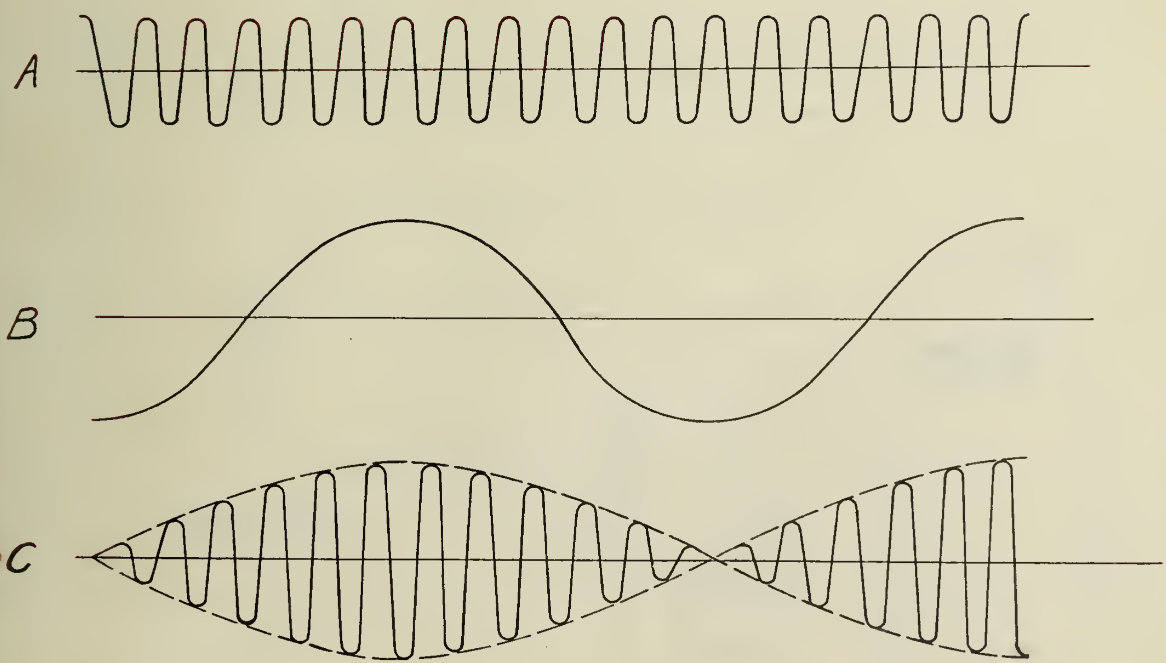


Fig. 68.

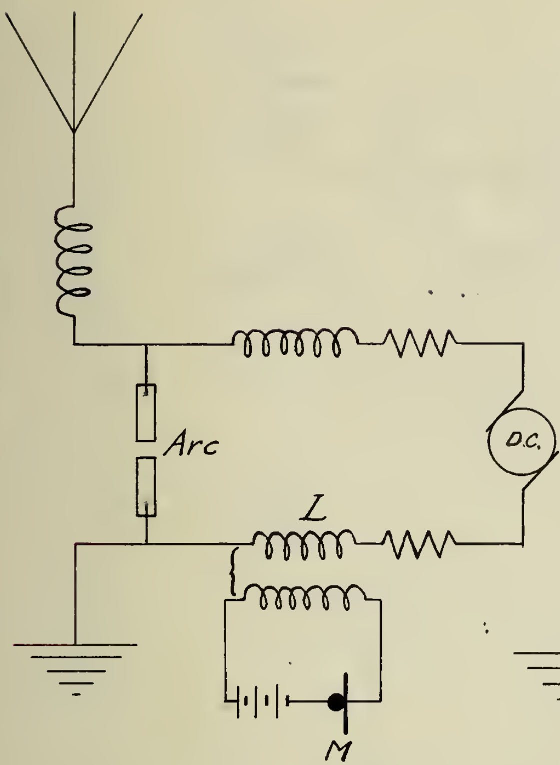


Fig. 69

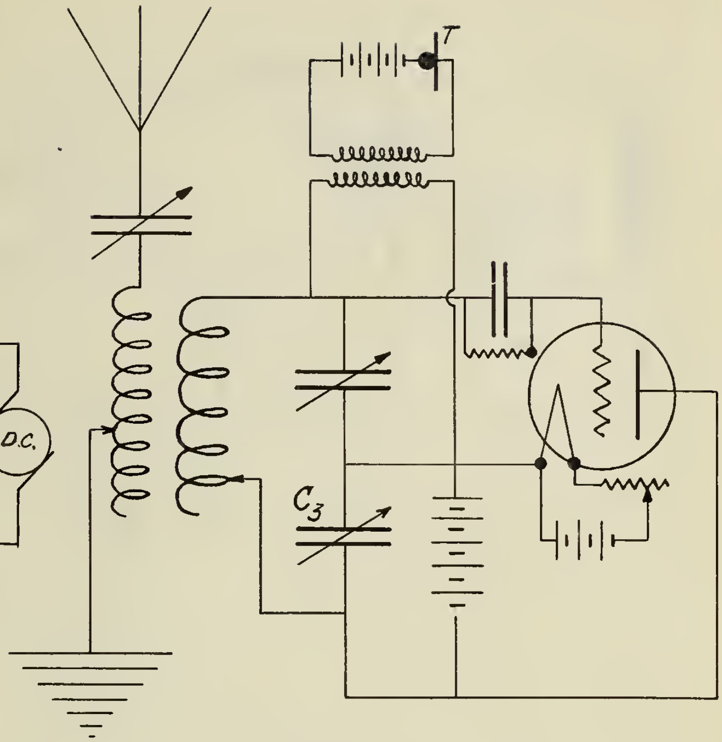


Fig. 70

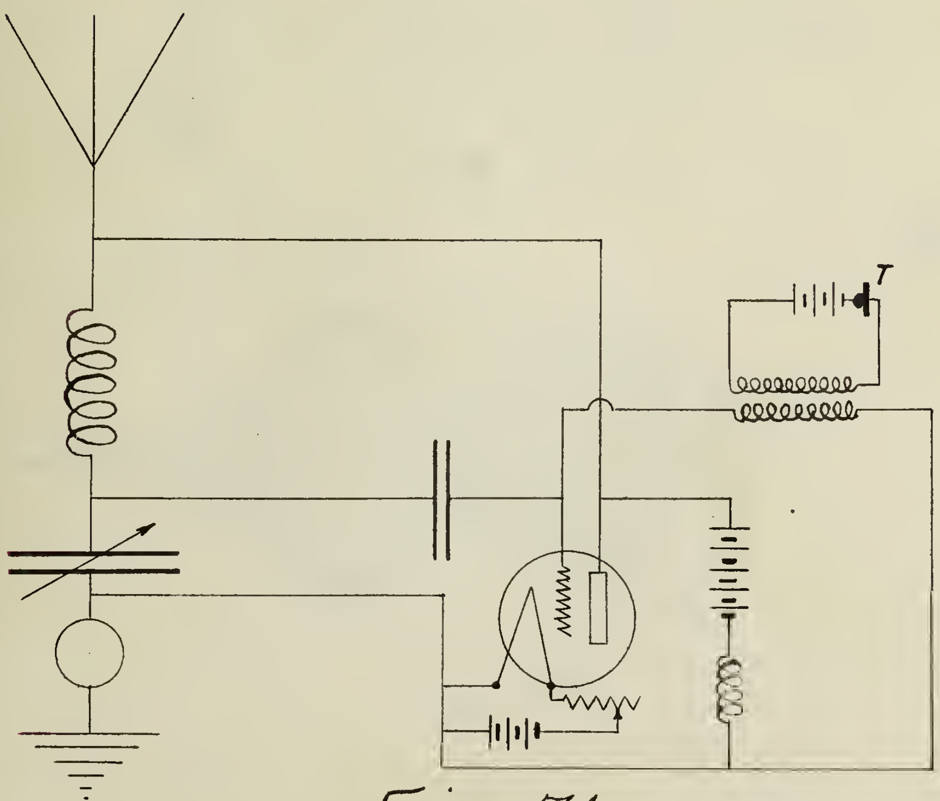


Fig 71.

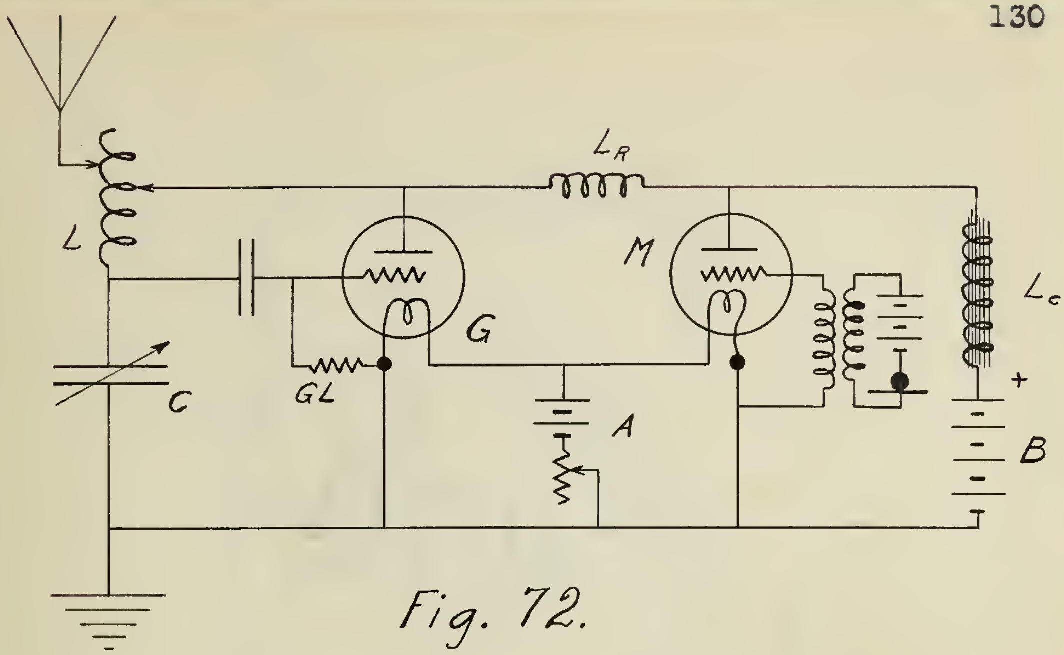


Fig. 72.

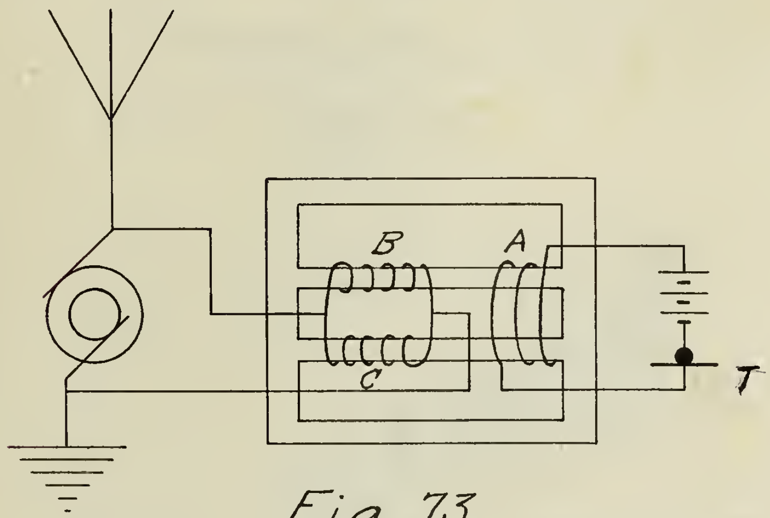


Fig. 73

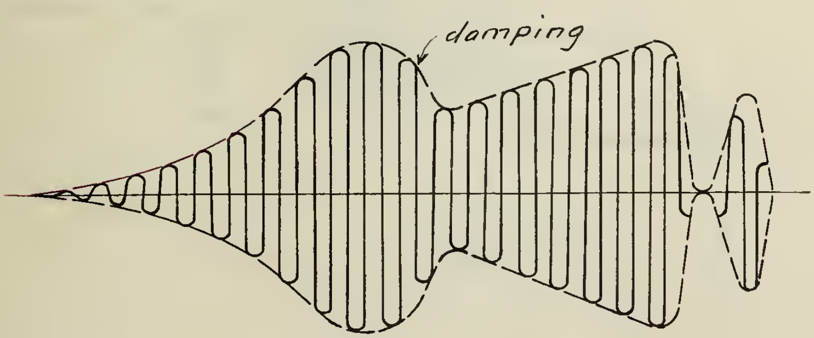


Fig. 74.

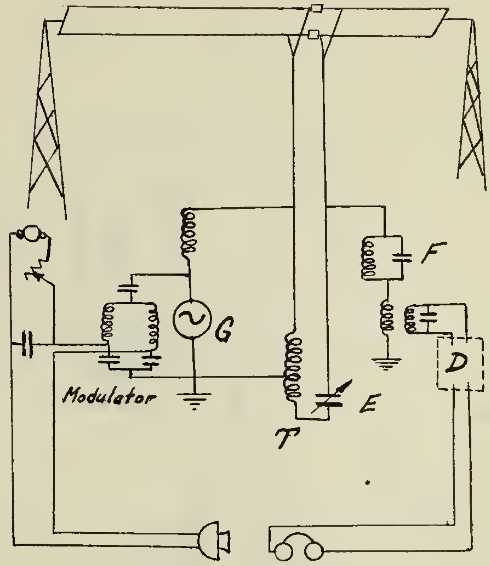

F
G
D
Modulator
E
T

Fig. 75.

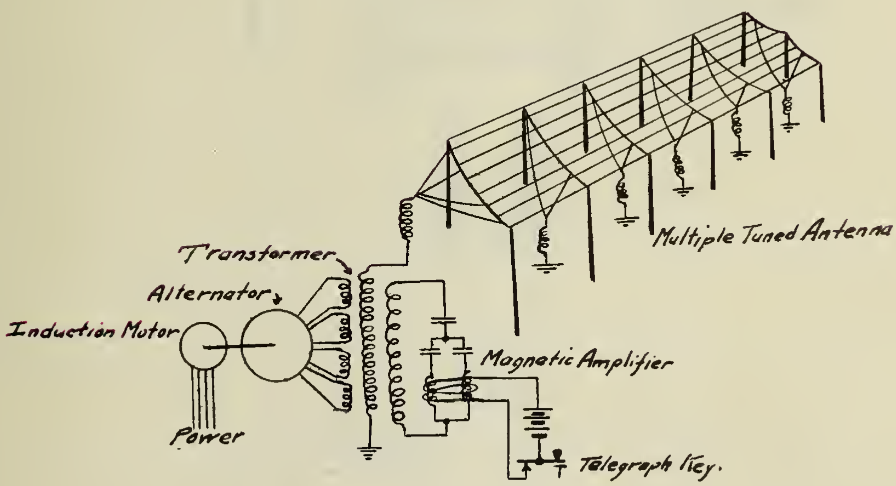
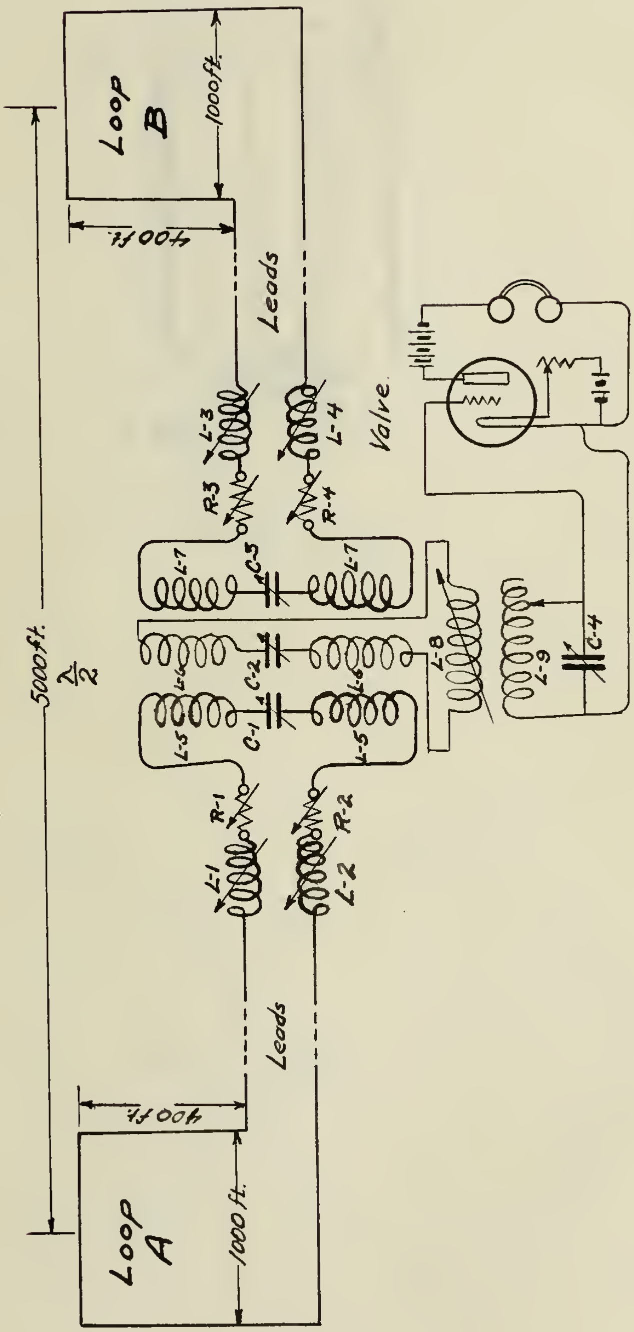

Multiple Tuned Antenna
Transformer
Alternator
Induction Motor
Magnetic Amplifier
Power
Telegraph Key.

Fig. 76.



Loop A
Loop B
1000 ft.
1000 ft.
400 ft.
400 ft.
Leads
Leads
5000 ft.
$\frac{\lambda}{2}$
L-1
L-2
L-3
L-4
L-5
L-6
L-7
L-8
L-9
R-1
R-2
R-3
R-4
C-1
C-2
C-3
C-4
Valve.

Fig. 77.

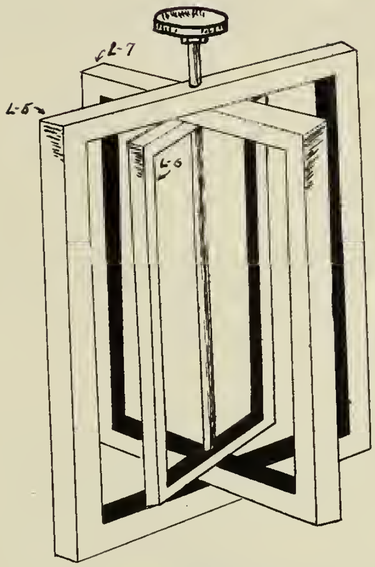


Fig. 78.

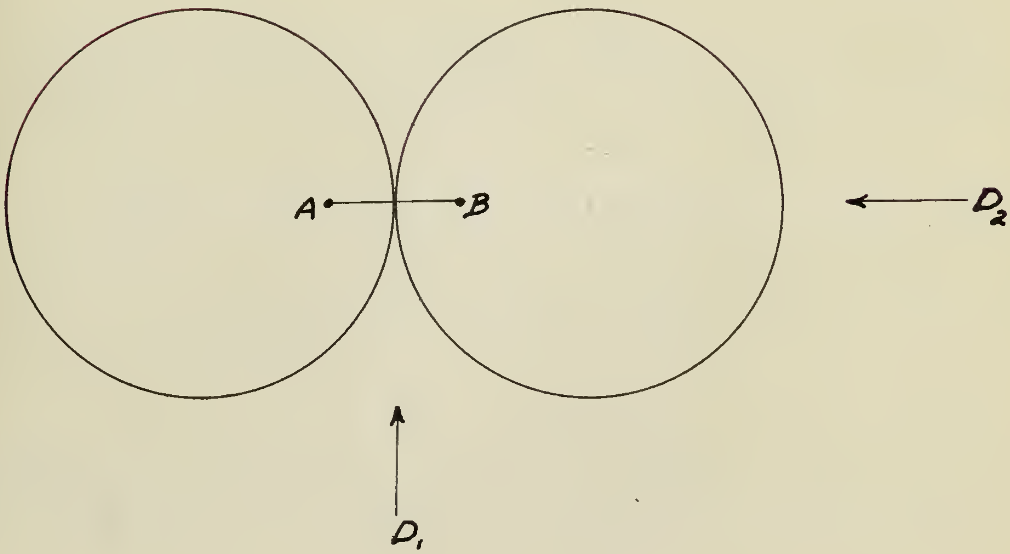


Fig. 79.

LABORATORY COURSE

I LABORATORY EXERCISES

EXERCISE NO. 1

RESONANCE CURVES OF OSCILLATORY CIRCUITS

Introductory.

If a condenser circuit is excited by a coupled oscillating circuit the amplitude of induced current in the former will vary with the capacity of its condenser. The curve between the current and condenser capacity is known as a resonance curve. The point of resonance is shown by the peak of the curve. In order that the peak may be sharply defined the square of the current values are plotted against condenser capacity. The sharpmess of resonance of the excited or receiving circuit is indicated by the shape of this curve.

Procedure.

1. The oscillating circuit should be excited by a buzzer and battery and all connections made as indicated in the diagram.

2. With circuit B loosely coupled to A adjust the detector until the buzz is distinctly heard in the receivers. Without disturbing the detector remove the receivers and connect a D'Arsonval galvanometer in series with the detector.

3. Vary the capacity of the condenser in B and also the coupling of A and B until the maximum deflection (at resonance) is almost of full scale value. This should occur with the setting of condenser B at about one half its full capacity. If this is not the setting for resonance change the capacity of condenser A and try again.

4. When the above setting has been made, be careful to not change the coupling or detector adjustment. Vary the capacity of the condenser D from zero to maximum and take fifteen readings of condenser scale setting and galvanometer deflection.

Be sure to take readings closer together as the deflections increase and decrease rapidly so as to get the peak point of the curve.

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

5. Open the short circuiting key and repeat with a resistance of about 5 ohms in circuit with A. Repeat for a value of resistance which will give a maximum deflection of one third the value obtained in (4).

Report.

1. Plot resonance curves as explained above.

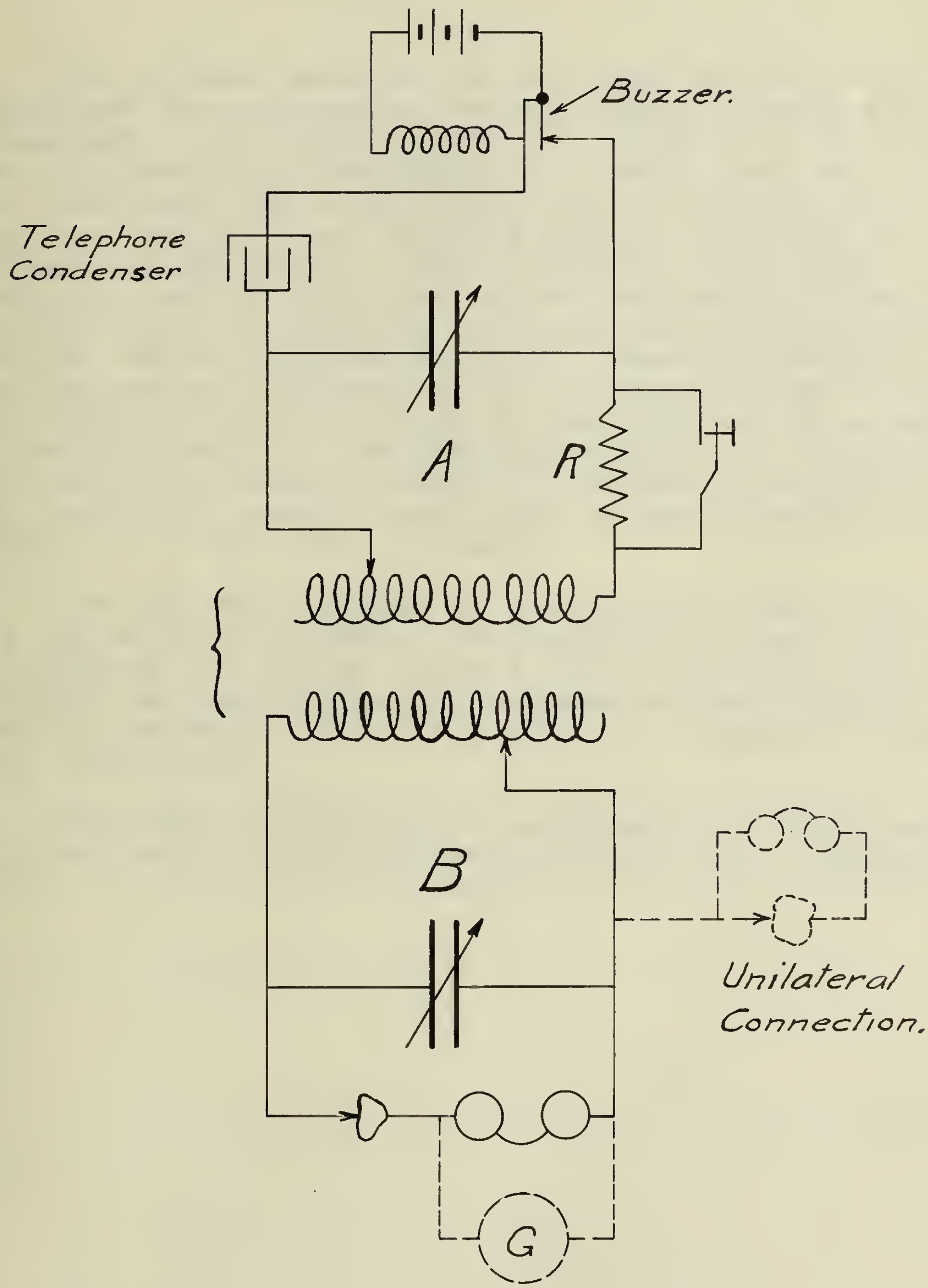
2. Explain why the peak is less sharply defined for larger values of resistance.

3. What would be the effect upon the shape of the curves if A and B were closely coupled? Why?

4. Explain the function of the buzzer in the circuit A.

References Mills p. 79 - 80
This Thesis p.

Connections Exercise No. 1.



APPARATUS FOR EXERCISE NO. 1

The silicon detector is much more satisfactory for this exercise than galena as its adjustment is more constant and permanent. The coupling coils of A and B in the diagram may be the primary and secondary of a small short wave loose coupler, the lower resistance coil being connected in circuit A. However, two small so called single or double slide tuners are the most satisfactory. Small variable condensers of .001 m.f. capacity may be used, but better results are obtained if a laboratory type of variable condenser is used having a calibration curve furnished with it. These condensers have calibration curves which are either straight lines or curved lines, depending upon the shape of the plates. If no calibration curve is available the resonance curves are plotted with readings of the condenser scale as abscissae, and the condenser must be one whose capacity variation is approximately a straight line function of the scale readings.

The currents induced in the circuit B are very weak, hence a hot wire milliammeter or thermocouple cannot be used. This is true of all buzzer excited circuits of the above type. These latter current indicating devices can be used if B is excited by a powerful oscillator such as a vacuum tube generator or spark transmitter.

Accurate results cannot be expected in this exercise, hence an accurate method will be used in a later exercise.

EXERCISE NO. 2

CONDENSER CALIBRATION CURVES

Introductory.

If a wavemeter be excited by a buzzer it will emit waves of a wave length determined by the reading of the instrument. If a known inductance and unknown condenser be connected together and coupled to the oscillating wave meter the values of λ in each condenser circuit will be equal when resonance is obtained. From this the capacity of the unknown condenser may be obtained.

Procedure.

1. Make connections as shown in the diagram placing the standard inductance (.05 m.h.) and the unknown condenser in circuit B with the detector and telephones shunted across the latter.

2. Vary the length of the emitted waves by varying the wavemeter condenser and find the position of the scale of the unknown condenser for resonance for each emitted wave length. Resonance is indicated by maximum sound in the receivers.

3. Calculate the capacity for each position of resonance of the unknown condenser.

Report.

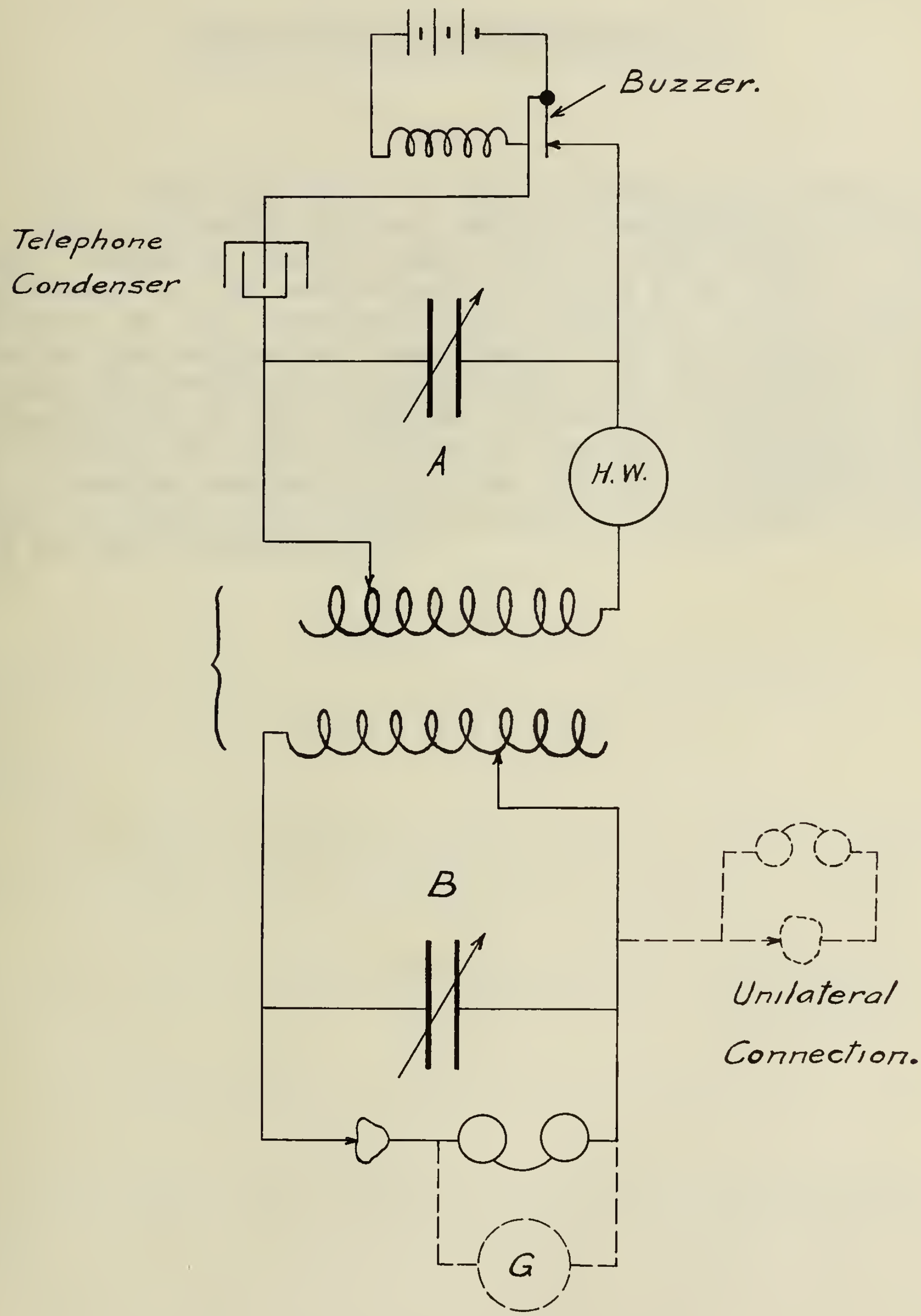
1. Plot a curve with condenser setting as abscissae and capacity as ordinates. Plot a curve also with wave length as ordinates.

2. Explain shape of curves.

3. Explain the method of obtaining the capacity of the unknown condenser.

References Bul. No. 74 Bureau of Standards p. 227, 252.

Connections Exercise No. 2.



APPARATUS FOR EXERCISE NO. 2

For this and many of the following exercises the General Radio portable direct reading wavemeter is well suited. Its range should be small, about 200 to 750 meters. A hot wire galvanometer is connected in series with the inductance and capacity of the wavemeter but cannot be used in this exercise as was explained previously. If the room is quiet a unilateral connection of the detector may be used as shown by the dotted lines in the diagram. However, the shunt connection does not cause an error that is of any consequence and gives much more marked resonance in most cases. A standard inductance of .05 m. h. such as is manufactured by the General Radio Company is very satisfactory.

EXERCISE NO. 3

MEASUREMENT OF INDUCTANCE AND CAPACITY OF AN ANTENNA

Introductory.

The wave length of an antenna may be measured readily by exciting it and finding the point of resonance of a coupled wavemeter. If a known inductance L_1 is put in series with the antenna the total inductance is the sum of the antenna inductance and that connected in series and the new wave length will be

$$\lambda = 2\pi v \sqrt{(L+L_1)\,C}$$

This principle may be used in separating the capacity and inductance of an antenna as follows:

Procedure.

1. Make all connections as shown in the diagram using a known inductance for the coupling coil, a small spark coil to excite the antenna and with wavemeter coupled as shown.

2. Set the gap so that the spark coil discharges and while it is operating adjust the wavemeter to resonance and read the wave length.

3. Substitute a larger known inductance and measure the increased wave length.

4. From the known inductances and wave lengths calculate the inductance and capacity of the antenna from the relation

$$L = \frac{\lambda_1^2 L_2 - \lambda_2^2 L_1}{\lambda_2^2 - \lambda_1^2}$$

L = inductance of antenna in heuries
L_1 and L_2 are smaller and larger added known inductances respectively
λ_1 and λ_2 are the wave lengths with L_1 and L_2 added respectively

Report.

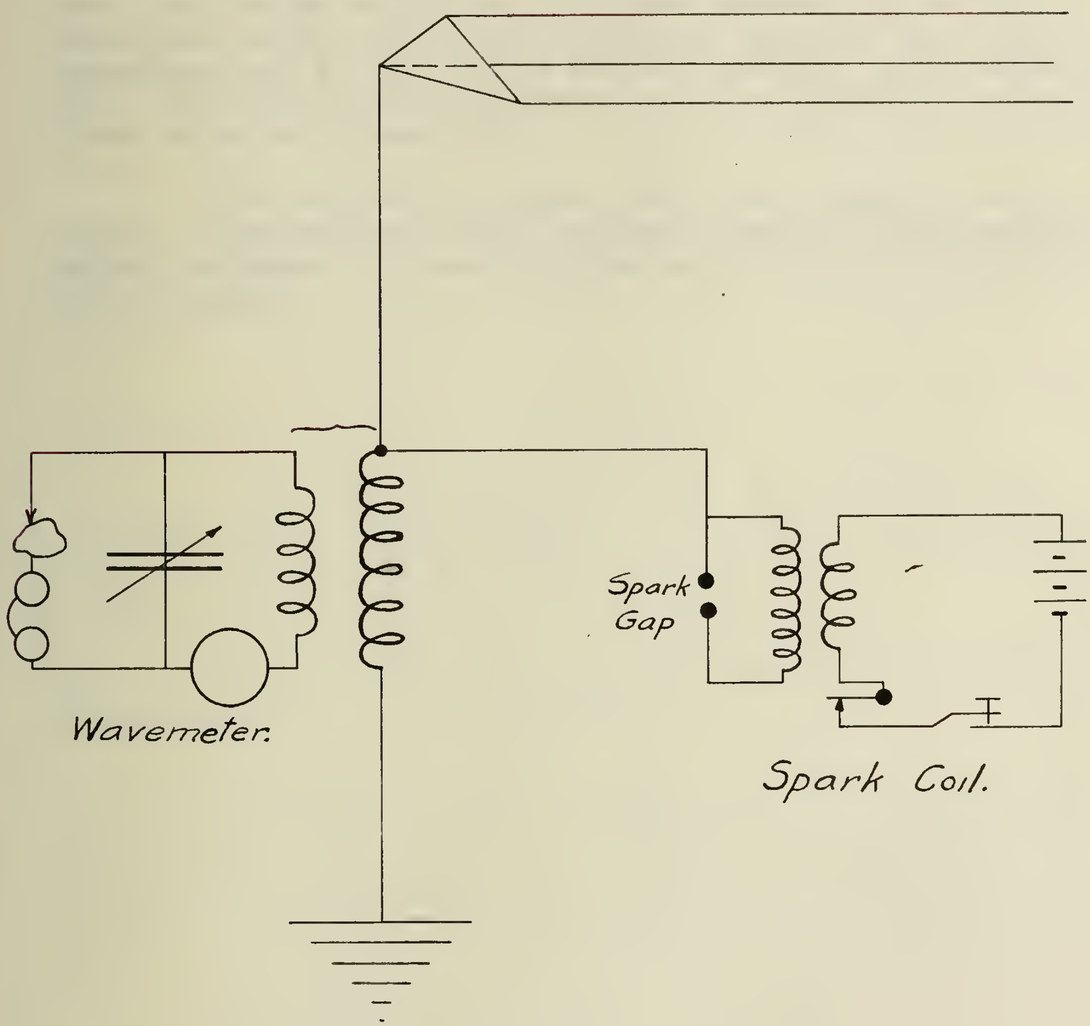
1. Derive the above formula

2. Could this measurement have been made by connecting different capacities in series? Why or why not?

3. Discuss sources of error in this test.

4. Give the ratio of the wave length of this antenna to its total length in meters.

Connections Exercise No. 3.



DISCUSSION OF EXERCISE NO. 3

The writer has found that for most antennas which have long wires an ordinary buzzer cannot cause it to oscillate with sufficient intensity to give any results. Experimenting with various devices showed that a small spark coil, especially the ignition coil for the Ford automobile gives excellent results.

The writer has also found that results are more readily obtained with this method than with the method using a large condenser and small inductance added in series respectively.

EXERCISE NO. 4

THE CURRENT-VOLTAGE CHARACTERISTICS OF A CRYSTAL DETECTOR

Procedure.

1. Connect an adjustable rheostat of suitable value across a source of 10 volts C. D.

2. Connect a milliammeter and a crystal detector in series and connect the combination from one end of the rheostat to the terminal of the sliding contact. Connect a voltmeter to read the voltage across the crystal and the milliammeter.

3. Connect a buzzer so as to excite inductively an oscillation circuit, a wavemeter or an equivalent circuit.

4. Temporarily disconnect the crystal from circuit 2-- and connect it unilaterally to the oscillation circuit, placing head phones in parallel with the crystal. Start the buzzer and adjust the crystal for sensitiveness.

5. Disconnect the crystal from circuit (4) and reconnect to circuit (2), being careful not to disturb the adjustment of the crystal in the slightest.

6. By shifting the slider of the rheostat impress a series of voltages on the crystal, in both directions, and read both meters. Range +5 to -5 volts. ± During this series of observations the adjustment of the crystal should not be disturbed, and the current should not be kept on the crystal any longer than necessary so as to avoid heating of the contact.

7. Repeat with other crystals.

TO FIND THE EFFECT OF A CONSTANT VOLTAGE ON A CRYSTAL DETECTOR

1. Connect a crystal as in (4) above, excite the buzzer, and adjust.

2. Connect a battery of 6 volts to the ends of an adjustable rheostat.

3. Run connections from one end of the rheostat and from the movable contact to the terminals of the crystal.

4. Connect a voltmeter to the same rheostat terminals as in (3). (Connect crystal and phone in series and across terminals of condenser).

5. Start the buzzer and find the magnitude and directions of the voltage impressed in the crystal that will give the loudest sound in the phones.

Report.

1. State the theory of the crystal rectifier.

2. Plot curves with voltages as abscissae and currents as ordinates. Interpret the curves to explain the action of the crystal as a detector.

DISCUSSION OF EXERCISE NO. 4

Verbal instructions are given the student in this exercise instead of a diagram of connections. This is intended to give the student practice in making connections without the aid of a diagram. A millivoltmeter may be used in this test in place of the milliammeter. As no measurements of resonance are taken in this test uniform results are easily obtained. A silicon or carborundum crystal is more satisfactory for this exercise due to the fact that the contact does not need to be as light as with some crystals, and hence there is less chance of change of adjustment.

EXERCISE NO. 5

THE RADIO TRANSMITTING CIRCUIT

Introductory.

The purpose of this exercise is to give the student experience in the connecting and operating of a radio transmitter. There are several minor features of importance in the connection and protection of the circuits that can be best understood by inspection of the circuits.

Procedure.

1. Connect all the transmitting apparatus in the station according to the standard form of inductively coupled transmitter described in Chapter III.

2. Operate the antenna switch and the spark gap motor switch. Close the key and vary the speed of the spark gap motor and note the effect. Vary the coupling and note the effect upon the radiation ammeter deflection. Vary the inductance and note the effect.

3. Twist the ground wire around into a one turn loop, place the wavemeter near this and note the maximum deflection of the hot wire galvanometer in the wavemeter. With the spark gap stationary and the electrodes near together note the double wave length radiated.

Report.

1. Submit a diagram of connections of the transmitter including wiring of transformer through key and switches to the power circuit. Also show control circuit of the spark gap motor.

2. Explain the function of the condensers and lamps shunting the primary of the power transformer.

3. What is the purpose of the lamp shunting the key? Of the stationary gap connected to the secondary of the power transformer?

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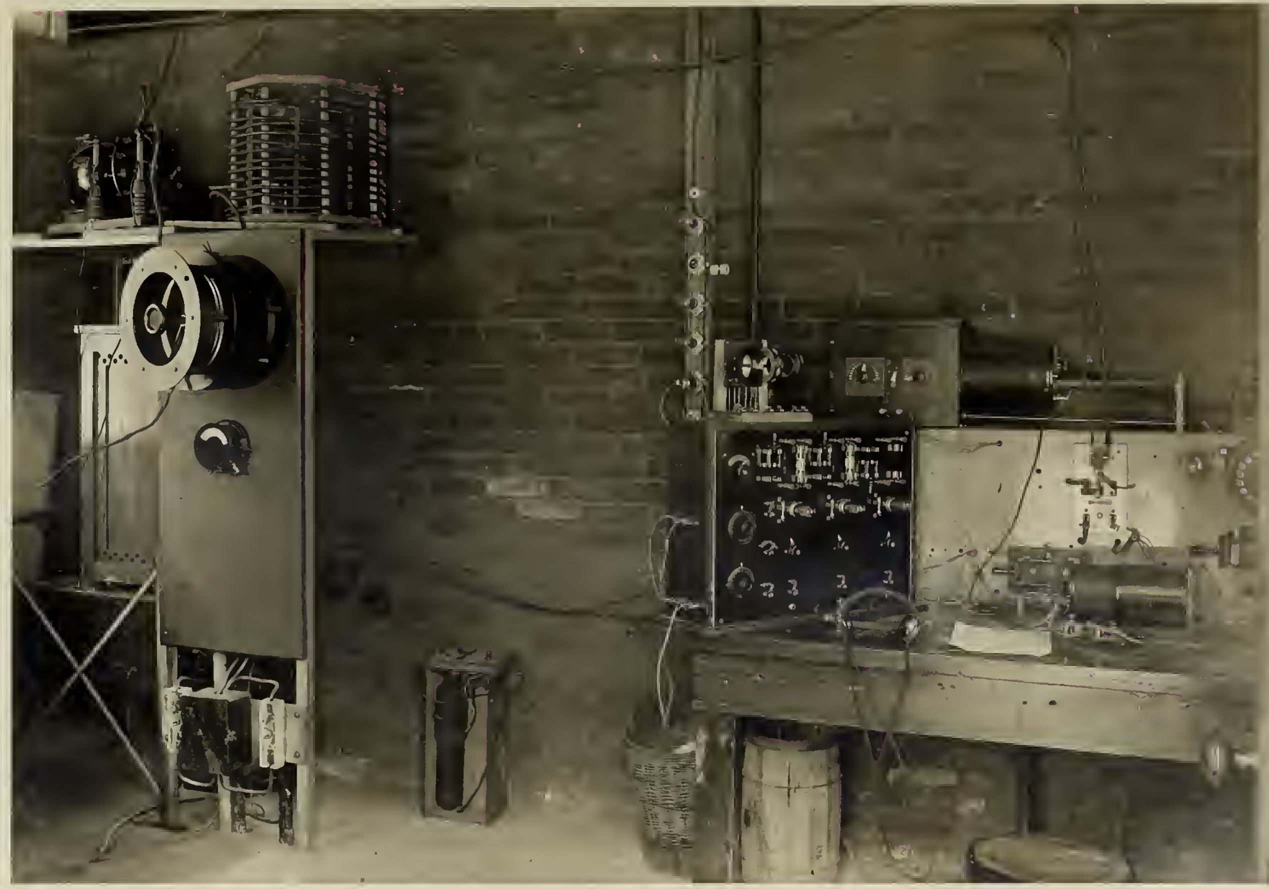


-Radio Station-
of
The Pennsylvania State College.

EXERCISE NO. 6

ADJUSTING AND TUNING TRANSMITTER

Introductory.

The first step in adjusting the transmitter is to adjust the natural wave length of the antenna to a required value, using a loading coil to increase it, if necessary. Next the wave length of the closed oscillating circuit is set to the same value by variation of inductance and capacity in this circuit. Lastly, the two oscillating circuits (antenna circuit and closed oscillating circuit) are coupled together with the oscillation transformer and the inductance, and coupling varied until a condition of maximum antenna current is obtained with the desired single, sharp wave length of the radiated wave.

Procedure.

1. Adjust the wave length of the antenna to 500 meters by connecting the proper turns of the antenna loading inductance and measuring its wave length by the method of Exercise #3 (Buzzer method). Obtain data for curves asked for under "Report".

2. Adjust the wave length of the closed oscillating circuit by operating the rotary gap, and varying the inductance in the primary of the oscillation transformer until the loosely coupled wave meter set at 500 meters gives maximum sound in the phones or maximum deflection on galvanometer.

3. The two oscillating circuits will now oscillate at 500 meters, and if very loosely coupled will be almost in resonance. Now loosely couple the two oscillating circuits by means of the oscillation transformer, and operate the transmitter. Vary the inductance in both primary and secondary of the oscillation transformer, and vary the coupling while listening to the radiated wave with wave meter and detector and phones until a sharp wave of 500 meters is radiated with maximum current flowing through the radiation meter in the antenna ground wire.

4. Record all values of current, turns in inductances, capacity of sending condenser, and watts input to transmitter for resonance (fully tuned).

Report.

1. State principles involved. State and explain all difficulties encountered in this test.

2. Plot a curve between turns in the antenna loading inductance and wave length of the antenna circuit. A similar curve for the primary circuit with varying numbers of turns in the primary of the oscillation transformer.

The intersection of these curves is theoretically the best wave length to which the station should be tuned. If the primary and secondary are so adjusted and coupled together it will be found that the transmitter will be not quite in resonance, and that resonance must be obtained by an additional variation of primary or secondary and coupling. Explain.

EXERCISE NO. 7

CHARACTERISTICS OF A "VT1" THREE ELEMENT VACUUM TUBE

Introductory.

The characteristics of a vacuum tube are shown by curves between grid potential (abscissae) and plate current for various values of plate voltage of the tube, and for values filament temperature. Slope of the rising part of the curve, increase in plate current to saturation point, and distance of saturation point from origin of abscissae all indicate its characteristics. The purpose of this test is to determine the characteristics of twp types of receiving tubes by obtaining data for the above curves.

Procedure.

1. Make connections to a Western Electric VT1 receiving tube as outlined in diagram. Impress a variable d.c.,e.m.f. on the plate and negative terminal of the filament by means of a 200 ohm rheostat connected as a potentiometer. (110 D.C. on the potentiometer). Connect a milliammeter in series so as to measure plate current. Connect filament to a storage battery with ammeter and rheostat so that filament current will be 1.1 amperes. By means of another potentiometer impress a variable voltage between filament and grid. Arrange reversing switch so as to reverse voltage on grid voltmeter. Use voltmeter to measure drop from plate to filament and from filament to grid.

2. Adjust plate voltage to 50 volts, and starting with grid voltage at such a negative value as to give zero plate current, increase grid voltage in positive direction until saturation point is reached. Take readings for curves, grid voltage vs. plate current. Repeat for plate voltage of 30 and 10 volts.

3. Take a similar set of curves for an Audiotron tube at two different temperatures if time permits.

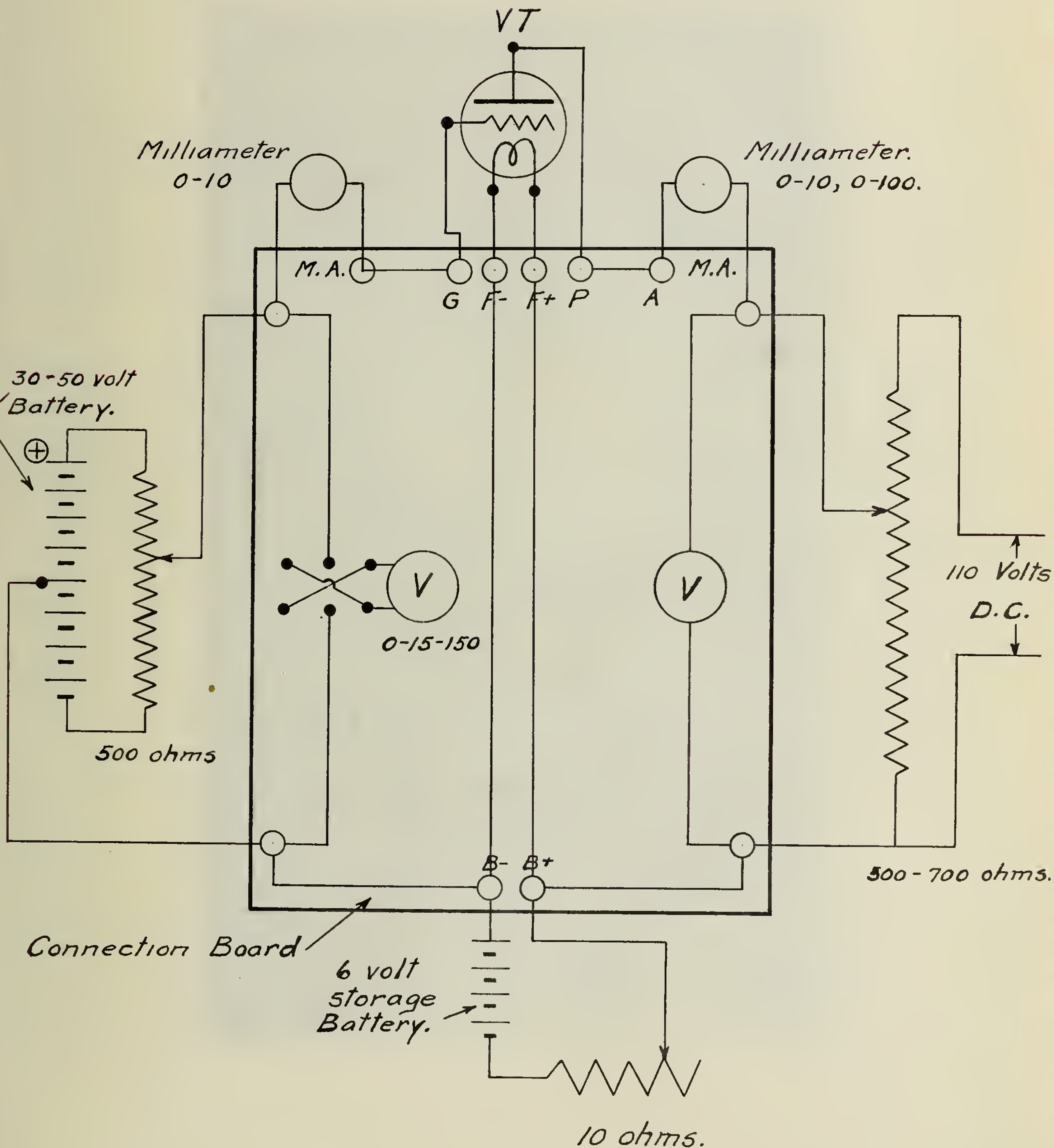
Report.

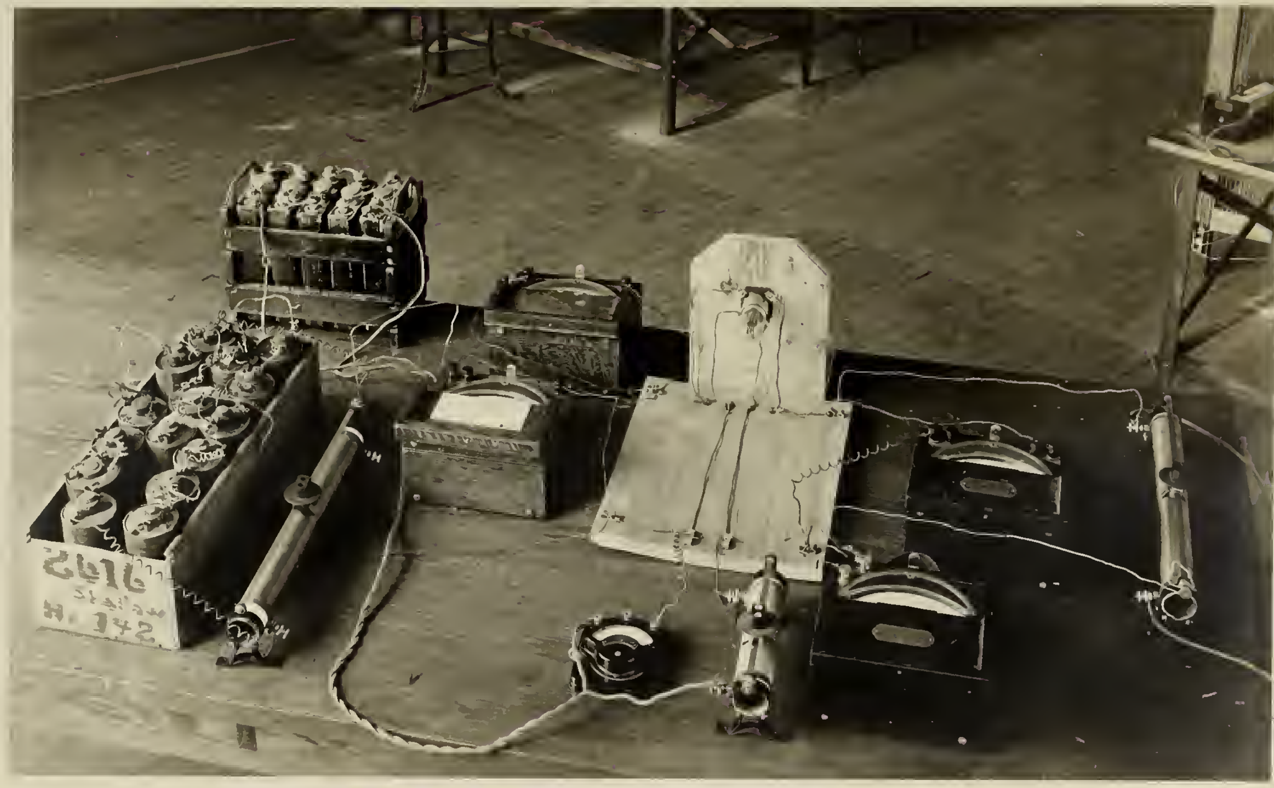
1. Plot curves, Accurate diagram.

2. Explain why the characteristic curve takes its peculiar shape.

References   This Thesis p.
Bulletin No. 74 Bureau of Standards
p. 200 - 204.

Connections - Exercise No. 7.





Set-up for Obtaining
Vacuum Tube Characteristic Curves.

APPARATUS FOR EXERCISE NO. 7

It is very necessary in this Exercise to have an orderly arrangement of the circuits so as to lessen the probability of a short circuit of either the grid or filament battery across the filament, which will of course burn out the latter. To facilitate this the writer made up a connection board the form of which is indicated in the diagram. Accompanying the diagram is a photograph of the complete set up of the apparatus. To facilitate making connections Fahnestock binding posts are screwed down to the connection board.

If a milliammeter is not available a millivoltmeter may be substituted but it should be calibrated so that curves may be plotted using plate current in milliamperes as ordinates. The current indicating device should have a low range, say 25 milliamperes at full scale deflection. The grid voltmeter may be one having zero at the middle of the scale. If this type is available the reversing switch shown in the diagram may be omitted.

EXERCISE NO. 8

OPERATION OF RADIO RECEIVERS

Introductory.

The receiver to be studied is so designed that several types of circuits may be obtained by the manipulation of two multipoint switches. By throwing double pole double throw switches different tubes may be alternately connected into the circuit. By plugging into various jacks the vacuum tube detector may be used alone or with a single stage or two stage amplifier. By the use of this apparatus the receiving efficiencies of various circuits, of different tubes, and of amplifiers may be quickly compared.

Procedure.

1. Trace the wiring of this receiver and draw diagrams of connections of the receiving circuit for each position of the upper four-point switch. Show the connections for one position of the tube double throw switches. That is, show the connections with just one set of tubes. Simplify the diagrams as much as possible.

2. Connect the receiver to the station antenna coupler, connect the batteries, as indicated by the terminals, and tune in an undamped wave station. Determine which type of circuit and which set of tubes give the best results.

3. Note: (a) the effect of varying plate voltage, and filament current for each set of tubes, (b) the effect of varying any of the inductances or capacities of the circuit upon the received signal, (c) the character of the note of one of the Navy spark stations sending out time signals, (d) comparative intensities when using single detector, one stage and two stage, amplifiers, (e) compare with a crystal detector listening to the time signals.

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[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

4. By connecting a plug type variable resistance in shunt with the telephones determine the relative audibility when using detector only, single stage amplifier, and two stage amplifier. The audibility is $\frac{S + t}{t}$ where t is the telephone impedance and S the resistance of the plug box necessary to make the signals just inaudible. The telephone impedance may be taken as its resistance, for this case 3200 ohms.

Report.

1. Submit the diagrams asked for.

2. Give and explain briefly the results obtained in (3) and (4).

(Note: This receiver is described in the appendix of this thesis).

EXERCISE NO. 9

THE VACUUM TUBE GENERATOR

Introductory.

The oscillations set up by the vacuum tube generator are of almost pure sine wave form and are undamped. If a wave meter be coupled to the oscillating circuit it will be noticed that the resonance is extremely sharp. The oscillations generated are much more powerful than with oscillatory circuits excited with a buzzer. This is shown by the fact that the hot wire galvanometer in the wave meter can be deflected off the scale when the wave meter is coupled closely to the oscillating circuit and adjusted to resonance.

Procedure.

1. Connect a VT2 transmitting tube to the 300 volt circuit of the dynamotor and with a storage battery to heat the filament. Make all connections as shown in the diagram. The oscillating circuit consists of the double slide tuning coil, the hot wire ammeter, and the two variable condensers in series. The wave length of the oscillations depends upon the adjustment of these two condensers and the sliding contacts of the coil.

2. Couple the wave meter to the inductance coil and adjust the circuit to give strong oscillations at various wave lengths. Note the sharp resonance. Vary the plate voltage and note the effect. Also the filament current. Caution: use care in making adjustments, do not touch bare contacts. If the deflection of the hot wire ammeter in the oscillating circuit suddenly falls off to a low value reduce the plate voltage by shutting of the dynamotor changing the condensers slightly and again bringing up the plate voltage. The inductance of the choke coil should also be varied for best results. It should be kept as large as possible to protect the dynamotor from high frequency oscillations. Watch the plate of the vacuum tube, do not let it get hot. Usually the heating of the plate is accompanied by the drop in oscillatory current.

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[illegible]

[illegible]

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[illegible]

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APPARATUS FOR EXERCISE NO. 9

The writer has found after experimenting with various vacuum tube oscillators that the circuit shown in the diagram is by far the most efficient of a number of circuits tried. It is a modification of that used in the Signal Corps Development Work during the war. The theoretical vacuum tube generator having a tickler coil in the plate circuit coupled to the grid circuit will function well as a regenerative receiver but is not a powerful oscillator. The above circuit will cause a deflection of .5 ampere in the oscillating circuit with 350 volts impressed on the plate of a Western Electric VT2 transmitting tube having an output of 5 watts.

The grid condenser in the diagram is necessary to keep the voltage of the dynamotor off the grid. It should have a capacity of not less than 0.1 m.f., and should be a mica condenser. The voltage will puncture a telephone condenser connected here.

The variable condensers should be of a type having heavy plates, and with the latter fairly well separated. The small variable condensers have thin plates very close together, and there is danger of a short of the high voltage d.c. supply.

The double slide inductance should be one wound with separated wires so that the sliding contacts do not short circuit two or more turns thus absorbing the energy. In case the tube discharges with a blue glow, or the plate glows at red heat something is wrong in the circuit, usually the grid condenser is short circuited. In case the reading of the hot wire ammeter suddenly falls to zero when the inductance coil or condensers are varied turn back the inductance or capacity from the direction in which it was being varied open the switch disconnecting the plate voltage and close it again or, better still, if the plate is being supplied by a dynamotor or d.c. generator reduce the voltage until the ammeter needle begins to rise slightly and increase it again. Sometimes the sudden decrease of oscillatory current is caused by too great a temperatureof the filament. Reducing the filament current a little below the theoretical value, 1.35 amperes, does not decrease the oscillatory current appreciably and gives steadier operation and longer life.

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[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

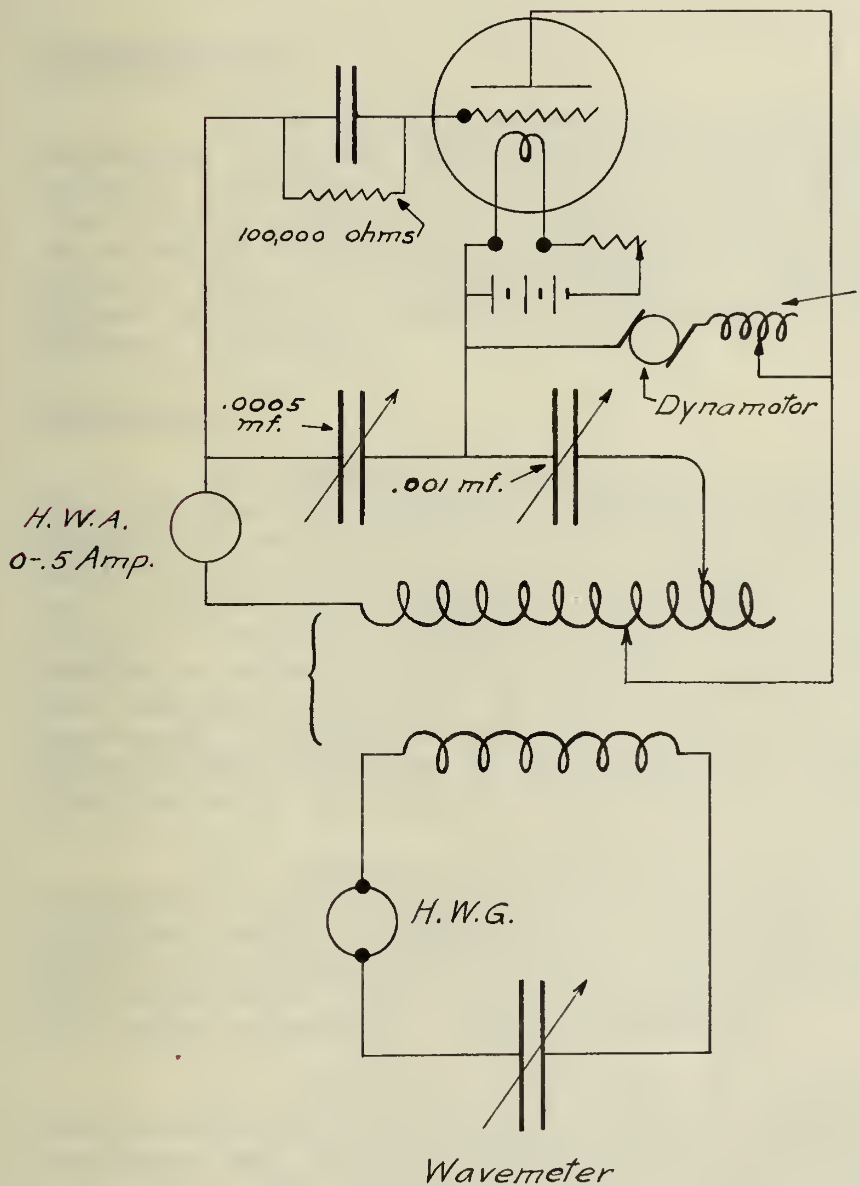
Report.

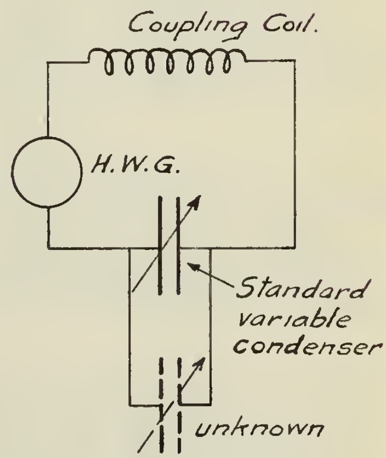
1. Describe the connection, operation, and adjustment of the generator.

2. Describe any other features or peculiarities and account for them.

3. Why does the deflection of the ammeter decrease slightly when the wave meter is brought into resonance with the oscillating circuit?

Connections Exercise No. 9.





Connections for Exercise No. 10.

EXERCISE NO. 10

MEASUREMENT OF CAPACITY-RESONANCE CURVES

Introductory.

If an inductance and known variable capacity are connected together and excited by coupling to an oscillatory circuit resonance is obtained when the capacity is adjusted to the correct value. If a second unknown capacity is connected in parallel with the first and the known capacity decreased until resonance is again obtained the difference between the former and latter known capacities is the capacity of the unknown condenser.

Procedure.

1. Connect an inductance, a hot wire galvanometer, and the standard variable condenser in series and couple loosely (half full scale deflection at resonance) to the vacuum tube oscillator of Exercise No. 9. Make adjustments on the oscillator circuit until resonance is obtained in the coupled circuit with the standard condenser set at its maximum capacity. A couple of short stiff wires should be fixed to the terminals of the standard condenser so that the unknown capacity may be connected in parallel without adding any wires. The addition of wires after resonance is obtained would change the capacity and inductance of the circuit and destroy resonance.

2. When all adjustments are carefully made for resonance of the coupled circuit note the reading of the standard condenser scale. Next connect the unknown inductance to the short protruding wires from the standard condenser and reduce the capacity of the latter until the hot wire galvanometer again indicates resonance. Note the reading.

3. Couple the wavemeter to the generator circuit and obtain data for a resonance curve by varying the wavemeter condenser and noting the reading of the hot wire galvanometer. Be sure to make adjustments so that data can be obtained for both rising and falling parts of the resonance curve. Vary the condenser capacity through its entire range.

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[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

Report.

1. Describe briefly the principle of this method of the measurement of capacity.

2. Give the capacity of the unknown condenser.

3. Discuss the accuracy of this method.

4. Why is the resonance curve obtained in this exercise very sharp? Why does the resonance curve obtained in Exercise No. 1 have a blunt peak.

APPARATUS FOR EXERCISE NO. 10

The standard variable condenser used in this exercise should be one of the large heavy plate type costing about $30.00. However, the writer has used with good results a small laboratory variable condenser furnished with the so called "vernier scale" and a calibration curve. The condenser is manufactured by the General Radio Company and costs about $14.00. The makers furnish the calibration curve.

This provides a very efficient and quick method of measuring small capacities and inductances. When measuring inductance the unknown is connected in series with the known. The accuracy obtained in this method is remarkable considering its simplicity, and for this reason will appeal to the student.

EXERCISE NO. 11

LOGARITHMIC DECREMENT OF AN EMITTED WAVE - TWO METHODS

Introductory - First Method

If the emitted wave induces oscillatory currents in an inductance and capacity which are connected together the logarithmic decrement of the oscillation in the latter circuit is equal to the sum of the logarithmic decrements of the emitted wave and that of the excited circuit. If a hot wire galvanometer is connected in series with the inductance and capacity of the excited or measuring circuit its deflection will be proportional to the square of the current. If C_r, C_1 and C_2 are respectively the capacities that produce full deflection at resonance and half deflection on either side of resonance

$$d_1 + d_2 = \frac{\pi}{2} \left(\frac{C_1 - C_2}{C_r} \right)$$

d_1 is the logarithmic decrement of the emitted wave, amd d_2 that of the measuring circuit.

The value of d_2 can be quickly found by repeating the above for the wave emitted by the vacuum tube generator of Exercise No. 9. Then

$$d_2 = \frac{\pi}{2} \left(\frac{C_1^{\,1} - C_2^{\,1}}{C_r^{\,1}} \right)$$

Procedure.

1. Form a "decremeter" by connecting the standard variable condenser, a small inductance and a hot wire galvanometer in series. The latter should have even scale divisions from 0 to 100. Operate the rotary gap at the speed which gives a clear note, and close the transmitting key. Loosely couple the "decremeter" to a one turn loop of the antenna ground wire and note the capacity for maximum deflection of the galvanometer. Obtain the capacities for half of the above deflection on either side of resonance and calculate $d_1 + d_2$

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

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[illegible]

[illegible]

[illegible]

2. Repeat for the wave emitted from the vacuum tube generator and calculate d_2.

Procedure - Second Method

Couple the wavemeter to the one turn loop of the antenna ground wire, vary the condenser of the wavemeter through its full range and take readings of galvanometer deflection and wave length readings of the condenser scale.

Plot a resonance curve between

$\frac{d}{d_r}\left(=\frac{I^2}{I_r^2}\right)$ and $\frac{\lambda_r}{\lambda}$ as abscissae where

d_r and λ are deflection and wave length reading on scale at resonance. Draw the resonance ordinate and lay off the distances x and y as shown on the diagram. The logarithmic decrement is

$$d_1 + d_2 = 2\pi x\sqrt{\frac{y}{1-y}}$$

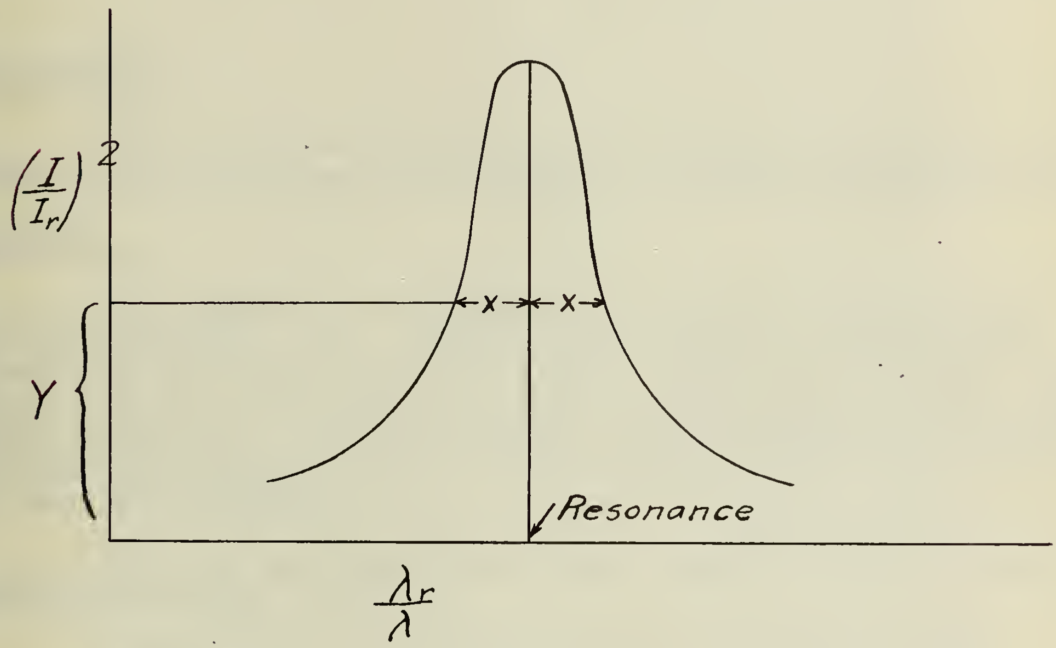
Calculate for different values of 2x (different heights) and check. Determine d_2 as before.

Report.

1. Calculate the value d_1 for each method, give the results and compare. Which seems to be the more accurate?

2. What would be the result if the decremeter or wavemeter were influenced by the primary circuit of the transmitter? Why is d_1 zero in the determination of d_2?

Diagram For Determining The Logarithmic Decrement, Second Method - Exercise No. 11.



EXERCISE NO. 12

CONNECTION AND OPERATION OF A RADIOPHONE USING LOOPS

Introductory.

This exercise will give the student practice in the actual construction and adjustment of simple radiophone circuits.

Procedure.

1. Connect a radiophone circuit as shown in Fig. 70 page129 of Chapter VII. Connect the transmitting loop in series with the oscillatory circuit. Connect the vacuum tube receiver to the second loop and place each loop so that their planes coincide. Tune the receiver while some one is speaking into the microphone. Adjustments must be made until the speech is clear and distinct.

2. Try out the double tube circuit shown in Fig.72 page130 of Chapter VII.

Note: Use the 250 volt battery instead of the dynamotor in this exercise.

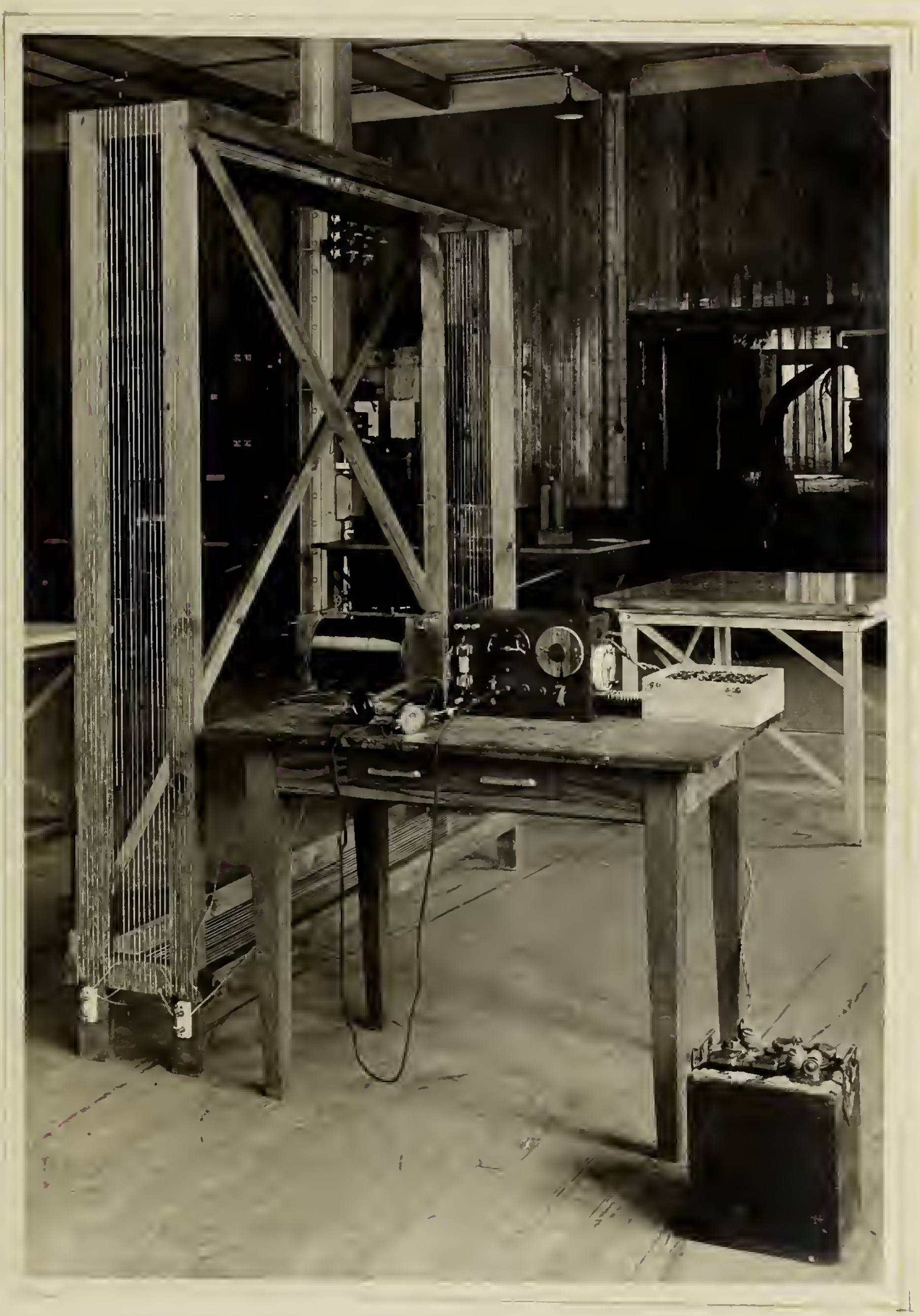
3. Measure comparative audibilities.

Report.

1. Explain the operation of the first circuit.

2. How did the circuits compare in efficiency?

Laboratory Radiophone Transmitting Apparatus.



Laboratory Loop Receiver.

APPARATUS FOR EXERCISE NO. 13

If the 250 volt battery is not available a filter must be used to eliminate the noises of the commutator. This may consist of a heavy choke coil connected in series with each terminal of the dynamotor. Each choke is shunted by a 2 m.f. condenser. A 4 m.f. condenser is connected across the terminals of the dynamotor, and another of the same size shunts the line just beyond the choke coils. This gives fairly good results but is not as quiet as the battery.

The loops are six feet square and one foot wide having 25 turns of wire spaced one-half inch. A photograph of the apparatus is shown next to this page.

The adjustment of this circuit requires considerable care for good results. It will be found that with poor adjustment the speech is distorted and indistinct. If the needle of the hot wire ammeter jumps periodically the circuit will not transmit speech, and further adjustment must be made of the condensers and possibly of the grid leak resistance. If the needle falls to zero when the microphone is spoken into further adjustment is necessary. The telephone induction coil is preferably one having taps in the secondary winding so that the best ratio may be selected by trial. The modulation sometimes may be better effected by connecting the secondary of the telephone induction coil in series with the grid. When thus connected the radio frequency potentials reach the grid by a fairly low impedance path formed by the high distributed capacity of the induction coil.

Ia SUGGESTED ADDITIONAL EXERCISES

The twelve exercises outlined are designed to acquaint the student with fundamental principles. If the course extends over a year additional exercises in radio measurements may be assigned instead of special work as has already been mentioned in the Introduction. Such exercises may include the following:

(a) Calibration of the Receiver in the Radio Station of the School.

This can be efficiently done by exciting the system, preferably the antenna, by the vacuum tube oscillator connected with the transmitting loop. The wave length of the radiations can be determined easily with the wavemeter as the former is varied and the receiving system tuned to receive each wave length. A crystal or audion detector may be used in the receiving circuit, and the plate voltage of the oscillator tube should be provided by means of a d.c. generator so that the commutator frequency will provide audible detection of the undamped waves. Any desired wave length radiations can be set up, the receiver tuned in with this wave length, and the tuning points marked. This can be done for any desired wave length within the range of the oscillator. Oscillationsset up by a wavemeter excited with a buzzer are unsatisfactory for purposes of receiver calibration unless the antenna is small and its resistance very low.

(b) Directional Properties of Loops.

The transmitting and receiving loop systems as previously described should be set up at as great a distance apart as possible, and, beginning with the loops in the same plane, audibilities should be measured with the receiving loop in various positions about a vertical axis. A polar curve should then be plotted between angular position and audibility of received signals or commutator frequency of the oscillator tube plate circuit generator. The same data can be taken with the loop receiver while listening to the signals from the nearest high power Naval station instead of the laboratory transmitting loop. The receiver must in many cases have a two stage audio frequency amplifier to provide good audible signals.

(c) Comparison of Loop with Antenna for Receiving.

This exercise may be performed in several ways. One simple way is to listen to some distant high power station such as Arlington with antenna, and loop alternately, measuring the audibility in each case. The received currents in loop and antenna may be calculated from formulas given by Dellinger, Proc. A. I. E. E.

October, 1919. The ratio of audibilities may then be compared to the ratio of calculated values of received current for antenna and loop. The direct measurement of received current is somewhat difficult, and in the writer's opinion is not advisable as a student exercise. For the above exercise the high frequency resistance of the antenna and loop may be calculated or even measured if a decremeter is available.

II DISCUSSION OF LABORATORY METHODS AND APPARATUS

I. Introductory.

All who are interested in radio laboratory work are more or less familiar with Circular No. 74, issued by the Bureau of Standards, entitled "Radio Instruments and Measurements". Teachers of radio laboratory courses should bear in mind that the methods described in the above bulletin may not be suitable for students who are unskilled in radio laboratory manipulations. In fact the bulletin has been compiled by laboratory specialists and research workers for use in radio research work. The discussions of theoretical principles and mathematical derivations are not sufficiently complete to be understood by the type of student for which this course is designed. The writer has attempted to prescribe the bulletin as a text and as a reference book to supplement lectures with very little success. The students often complained of it on the ground that they were unable to understand not only the discussions of mathematical and physical principles, but also of the description of laboratory procedures. Hence in the writer's experience it is unwise to adopt the bulletin for a text or for a laboratory manual.

II. Detector Connections to Indicate Resonance.

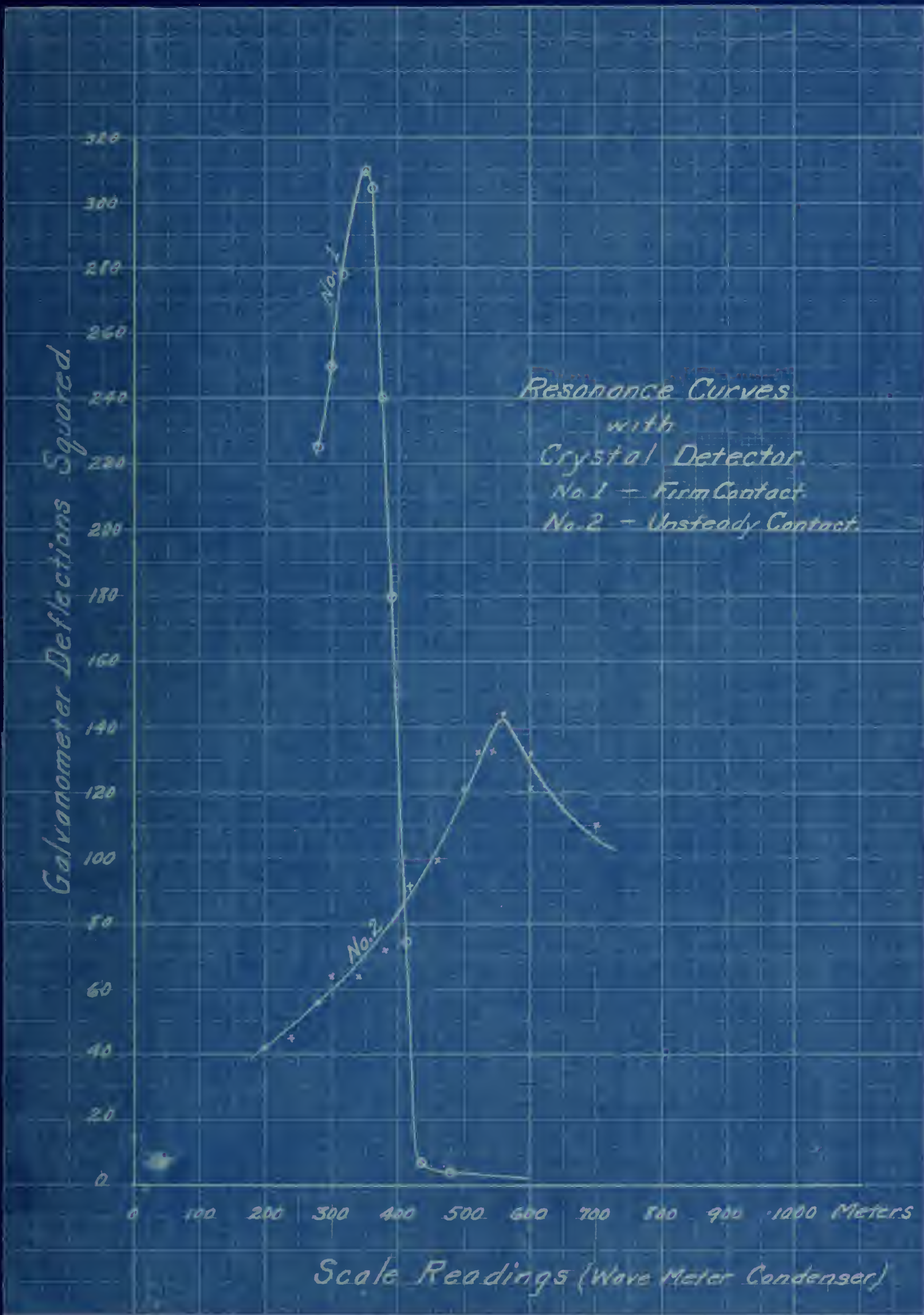
Much difficulty has been experienced by the writer in obtaining results when using the crystal detector and telephones to indicate resonance in an oscillatory circuit in a laboratory in which twenty five or thirty students were at work. Since in such circuits the resonance is not extremely sharp it was impossible to use the unilateral detector connection. In most cases sounds could not be detected at all on account of noise in the room. When the detector and telephones are connected in series and across the wavemeter condenser fairly good results are obtained owing to louder sound in the telephones permitting looser coupling of the wavemeter to the oscillatory circuit. Results of tests are given in Circular No. 74 to show that the unilateral connection gives the greater accuracy, but only by a very few per cent; however, when the great advantage in audibility of the shunt connection is considered the greater accuracy of the unilateral connection is not justified. The looser coupling permitted with shunt connection may often lead to greater accuracy with the latter as shown by the following simple test performed by the writer. A standard inductance of .05 millihenry and standard capacity of .000667 micro farads were

connected together and excited by a Century buzzer. A General Radio direct reading wavemeter, range 200 to 700 meters, was used to determine the wave length of the oscillations in the above oscillatory circuit. The wave length was measured first with the detector and telephones connected unilaterally to the wavemeter, and then with shunt connection. For the unilateral connection the wave length reading for resonance was 350 meters and for the shunt connection 340 meters while the correct wave length was approximately 345 meters indicating a little greater accuracy with the shunt connection. Very short leads were used between condenser and inductance to reduce error due to leads. A test was also made for comparative audibilities by the method of determining audibilities as described on page 166 of Circular No. 74 previously mentioned. With a constant value of coupling of the wavemeter the audibility was 18.6 for the shunt connection of the detector and telephones, and 2.9 for the unilateral connection. This shows approximately three times as great audibility for the former. Herein lies the great advantage of the shunt connection, as mentioned above.

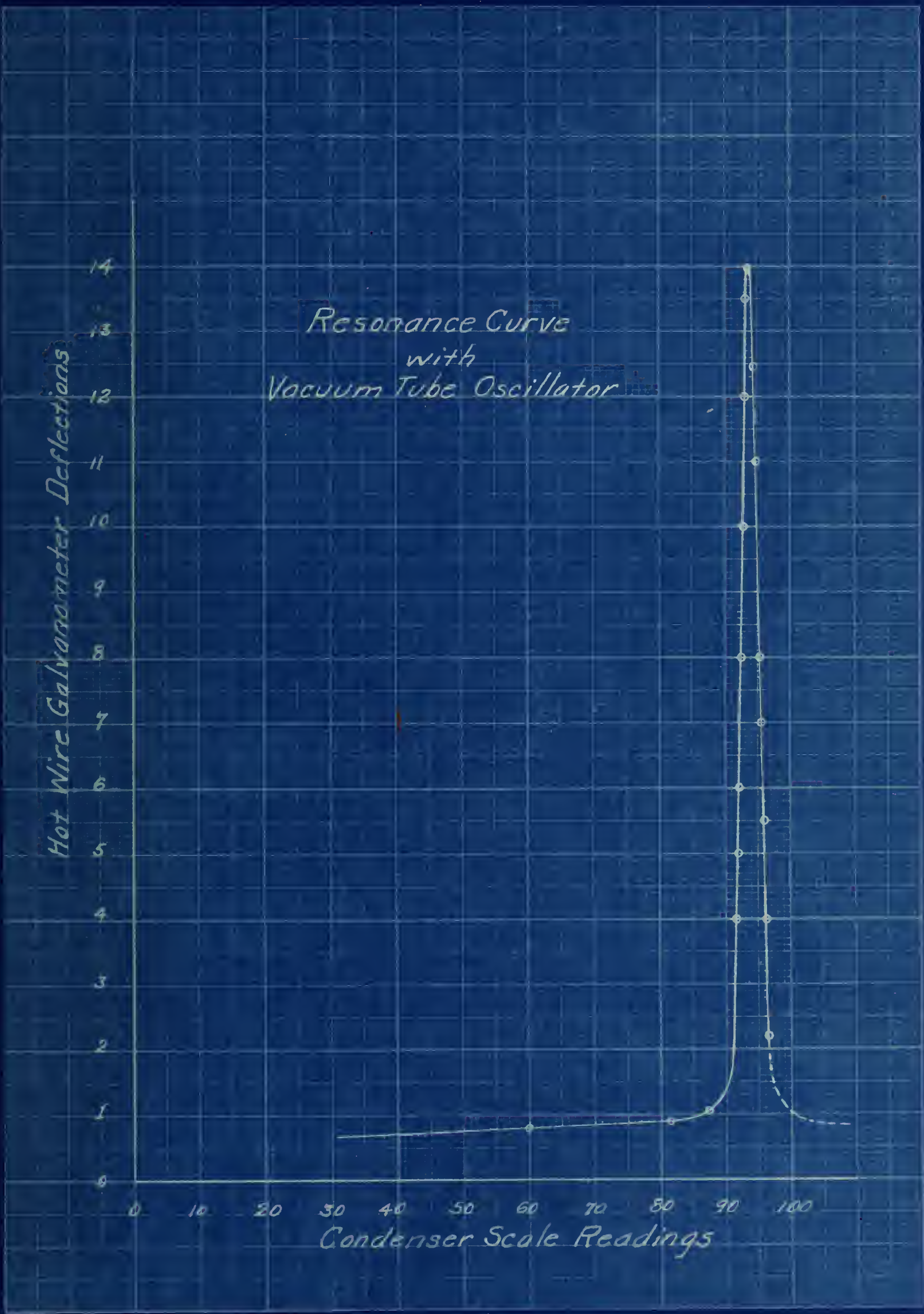
Considerable difficulty was encountered in obtaining resonance curves by the method of Exercise No. 1. In order to obtain data that will give a smooth curve the writer found that it was necessary to excite the oscillatory with a good type of constant amplitude buzzer, such as the Century buzzer, to have a carefully adjusted D'Arsonval galvanometer, and to have a crystal with a clean surface and firm contact. For this purpose a silicon detector gives the best results. This type of detector is most commonly used in wavemeters. The curve sheet next to this page shows the results of a light unsteady crystal contact. The data for these curves was taken by students in the laboratory while performing Exercise No. 1.

III. Vacuum Tube Oscillators.

The laboratory vacuum tube oscillators described in Circular No. 74 are of a complicated form in most cases and are more suitable for use with high power tubes. There are many possible combinations for vacuum tube oscillators but only a very few are efficient when operated on short wave lengths. The writer has experimented with several types of oscillators and has found the circuit described in connection with Exercise No. 9 to be the most satisfactory for the range of the 100 to 900 meters. This is the best range for measurements of the small capacities used in radio laboratories for receivers, wavemeters, etc. As stated in the discussion of Exercise No. 9 currents of .5 ampere are obtainable using one Western Electric transmitting tube. A typical resonance curve obtained in a wavemeter circuit coupled to this oscillator is shown on the curve next to this page. The data for this curve was obtained by a student in performing Exercise No. 9.



Resonance Curves
with
Crystal Detector
No. 1 - Firm Contact
No. 2 - Unsteady Contact
Galvanometer Deflections Squared
320
300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0
No. 1
No. 2
0
100
200
300
400
500
600
700
800
900
1000 Meters
Scale Readings (Wave Meter Condenser)


Resonance Curve
with
Vacuum Tube Oscillator
Hot Wire Galvanometer Deflections
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
0
10
20
30
40
50
60
70
80
90
100
Condenser Scale Readings

For longer wave lengths several types of oscillators may be used with fair success. In using oscillators two very important precautions should be taken. It is very necessary to insert one half ampere fuses in the high voltage battery circuit, and in series with the hot wire ammeter in the oscillating circuit. It often happens that a variable or fixed condenser short circuits resulting in disaster to the apparatus especially the hot wire ammeter. When using Western Electric transmitting tubes it is absolutely necessary to insulate the grid from the high voltage battery with condensers of rather large capacity and preferably of the mica type. If telephone condensers are used three should be connected in series, one alone is invariably punctured by high voltage. If the grid is not so insulated a blue discharge occurs in the tube which makes it useless as an oscillator. Many oscillators described in text books do not provide for this.

SUMMARY

I. Lecture and Recitation Course.

In the eight chapters devoted to the subject the most important fundamentals of oscillatory and resonant circuits as they apply to radio transmission and reception are dwelt upon, and the latest important developments in present day American radio engineering practice are briefly described. The mathematical principle is in nearly all cases preceded by a physical explanation of the phenomena under discussion. A more detailed account of the manner of treatment of the subject matter is given in the Introduction.

The writer desires to express the hope that his judgment as to what the most important fundamentals are is correct, and that he has made the material not only instructive but also interesting to the reader. It is also hoped that other instructors will make use of the material included in this thesis.

II. Laboratory Course.

The writer has had some discouraging experience in making up a laboratory course, and has selected for this course those exercises which have proven by experience or by special experiment to be the most satisfactory for the needs of the course. The writer believes that little difficulty will be encountered in the conduct of the exercises outlined if all instructions in the discussion of each exercise are followed.

APPENDIX

I. Special Receiving Apparatus for Educational Institutions.

The ideal radio receiver for use in this course is one which serves as a sensitive practical receiver for use in the radio station, while at the same time being so arranged that the performance of different circuits, of different tubes, and reception at different wave lengths can be quickly and easily compared. Commercial cabinet receivers lack the first two qualities mentioned. They are built and permanently wired so that one type of circuit only is provided for reception of undamped waves and one type provided for damped waves. It is very inconvenient to change the circuit, it means rewiring of the apparatus. One tube socket or set of tube sockets is provided, and will accommodate only one type of vacuum tube. Commercial receivers are built, however, to operate over a wide range of wave lengths, but such types are very expensive, and have the disadvantage that one particular type of receiving transformer which is built into the cabinet must be used. Furthermore the patent situation prevents manufacturers from combining many or all desirable features into the complete set. There is the final disadvantage that it is often difficult to insert calibrating apparatus, or measuring instruments into the circuits.

It is impracticable and inefficient to attempt to set up temporary changeable receiver circuits on account of complications, especially when amplifiers are used. Even if the detector and amplifier tubes are mounted in "control cabinets" wiring between the cabinets, to the batteries, and to the receiving tuner and change over switches makes a cumbersome set up. Accordingly the writer has designed a cabinet receiver which contains the desirable features mentioned for a college radio laboratory and station. Construction of the receiver was also carried out in the laboratory under the writer's supervision. In addition to the above features economy of space, light weight commensurate with flexibility, and low first cost were striven for.

This receiving cabinet contains receiving circuit variable condensers, a vacuum tube detector and a two stage audio frequency amplifier together with all necessary accessories. It is arranged to be connected to a separate receiving transformer or loose coupler. There are two reasons for doing this:

First, the cost of the cabinet incorporating a thoroughly flexible short wave and long wave receiving transformer is much greater than if it were omitted; and second, it was desired to provide means for using different types using the same cabinet and circuits.

Photographs showing the front and back of the cabinet are shown next to this page. Two sets of vacuum tube holders accommodating socket type or tubular type tubes are provided and either set may be put into use by manipulating the double pole double throw switches at the top of the panel. One type of tubes may be used as detectors and amplifiers, or a certain type may be used as a detector and a different type as amplifier tubes. If it is desired to compare two different kinds of socket tubes extra tube sockets may be connected to the binding posts for the tubular tubes. Telephone receiver connections are made by means of three jacks shown along the bottom of the panel. The back view shows a connection board to which many of the connections are brought. Fahnestock binding posts are provided on this board so that connections can be quickly made. By its use it is a simple matter to substitute different grid condensers, amplifying transformers, resistances, etc. Also new circuits may be conveniently connected. By means of the multipoint switch M and the "tickler" switch T four different circuits may be obtained, and each one of these used with or without amplifiers. If the detector only is to be used telephones are plugged into the jack to the left. The middle jack includes a single stage, and the jack on the right a two audio frequency amplifier. If several telephones or telephone and audibility meter are to be used the special intermediate plug shown in front of the cabinet is used. Filament current switches, rheostat knobs, grid leaks and variable condenser scales and knobs are shown.

A schematic diagram of the circuit omitting the tube changing feature is shown in Fig. 80. When the multipoint switch M is on point 1 and tickler switch T is to the right the receiver is set for damped waves, straight detector circuit. When T is turned to the left it is set for tickler coil regenerative reception of undamped waves. With T to the right and M on point 2 the "ultraudion" undamped circuit is in use. With M on point 3, T to the right the circuit is regenerative with capacity coupling of grid and plate circuits. A different capacity coupling circuit is obtained by changing the connection to the secondary tuning condenser from A to B. This can be easily done on the connection board. This latter circuit is a very efficient form of regenerative receiver for damped or undamped long and short waves, but is not well adapted to use with amplifiers. Fig. 81 is a complete wiring diagram of the receiver. S_1, S_2 and S_3 represent the switches for changing tubes. The Table on page 177 shows the cost of material and parts of the receiver cabinet. This cost does not include vacuum tubes, or telephone receivers.

COST OF MATERIAL FOR CABINET RECEIVER

1 - Bakelite Formica Panel 18" x 24" x 3/16"	$5.17
3 - Double pole double throw switches	1.50
6 - Army and Navy switch levers	2.88
1 1/2 doz.- Nickel plated switch points	.60
3 - Porcelain base rheostats	2.10
3 - Bakelite knobs for rheostats	.39
22 - Binding posts	1.98
3 - Bases for V. T. type tubes	4.50
3 - Marconi grid leaks	2.85
3 - Closed circuit telephone jacks	1.95
2 - Federal amplifying transformers	14.20
2 - Murdock fixed condensers	1.40
1 - De'Forest variable grid condenser	5.50
2 - Clapp Eastham balanced type variable condensers	19.00
2 doz.- Fahnestock binding posts	1.20
1 - Oak cabinet, Mission finish	4.00
Total cost	$69.22

Cabinet Receiver

Schematic Diagram

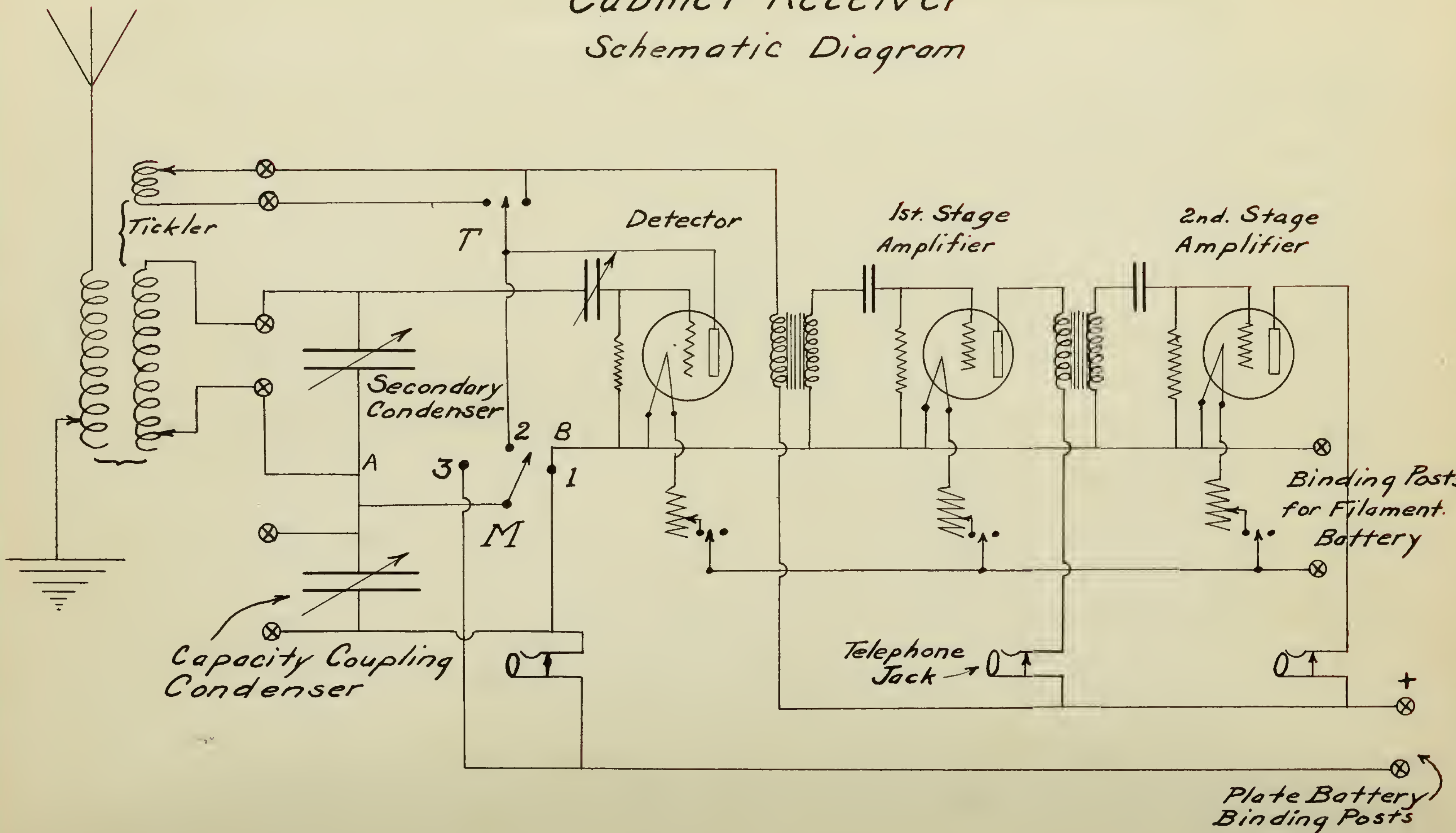
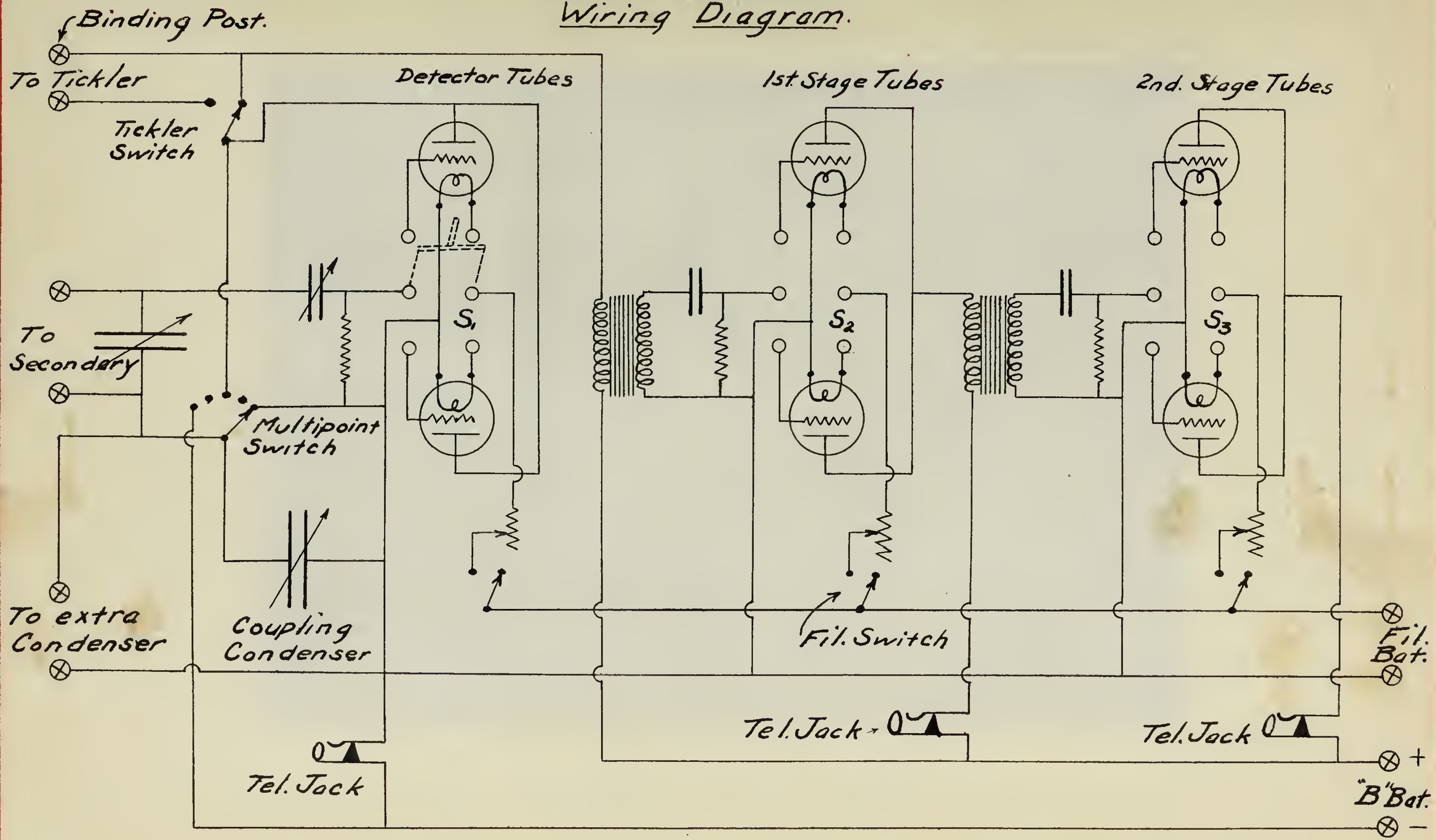
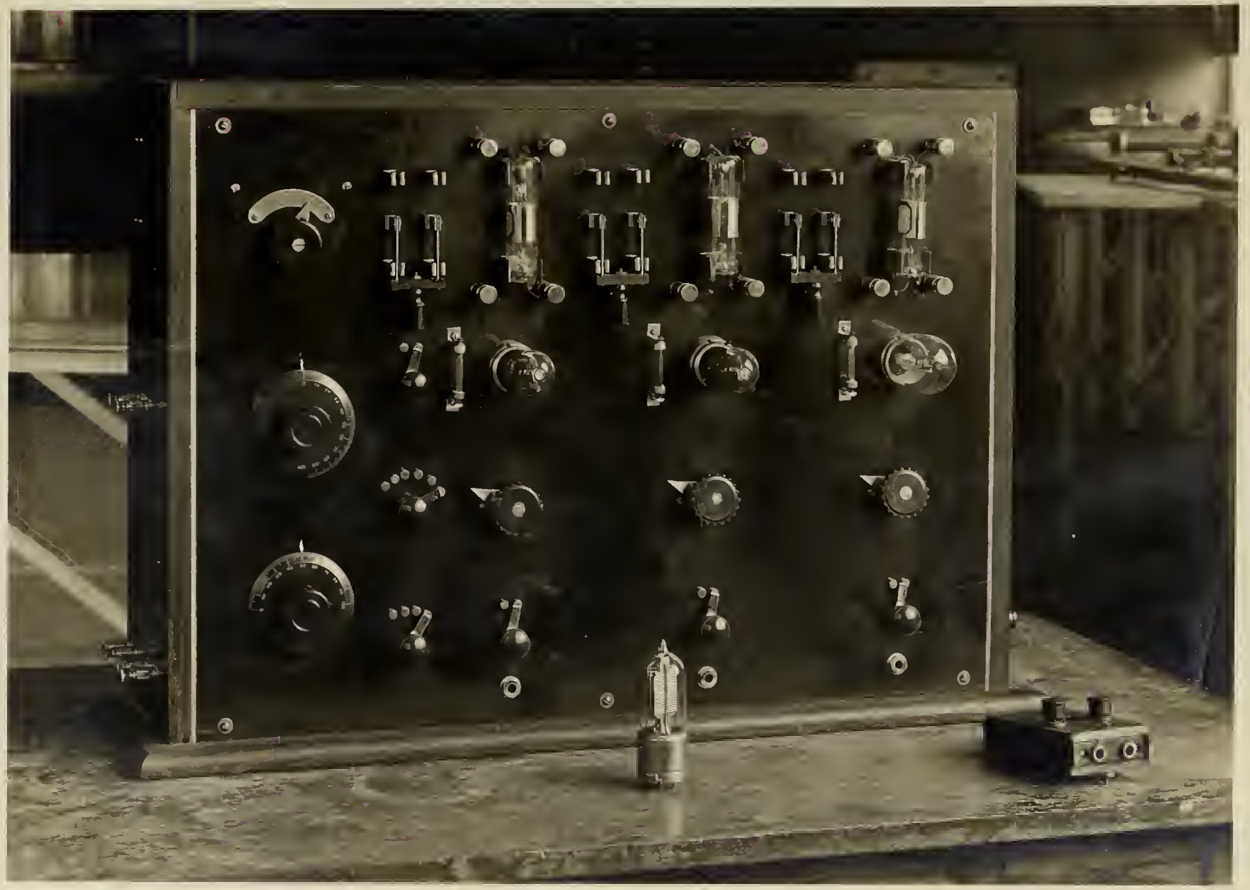


Fig. 80.

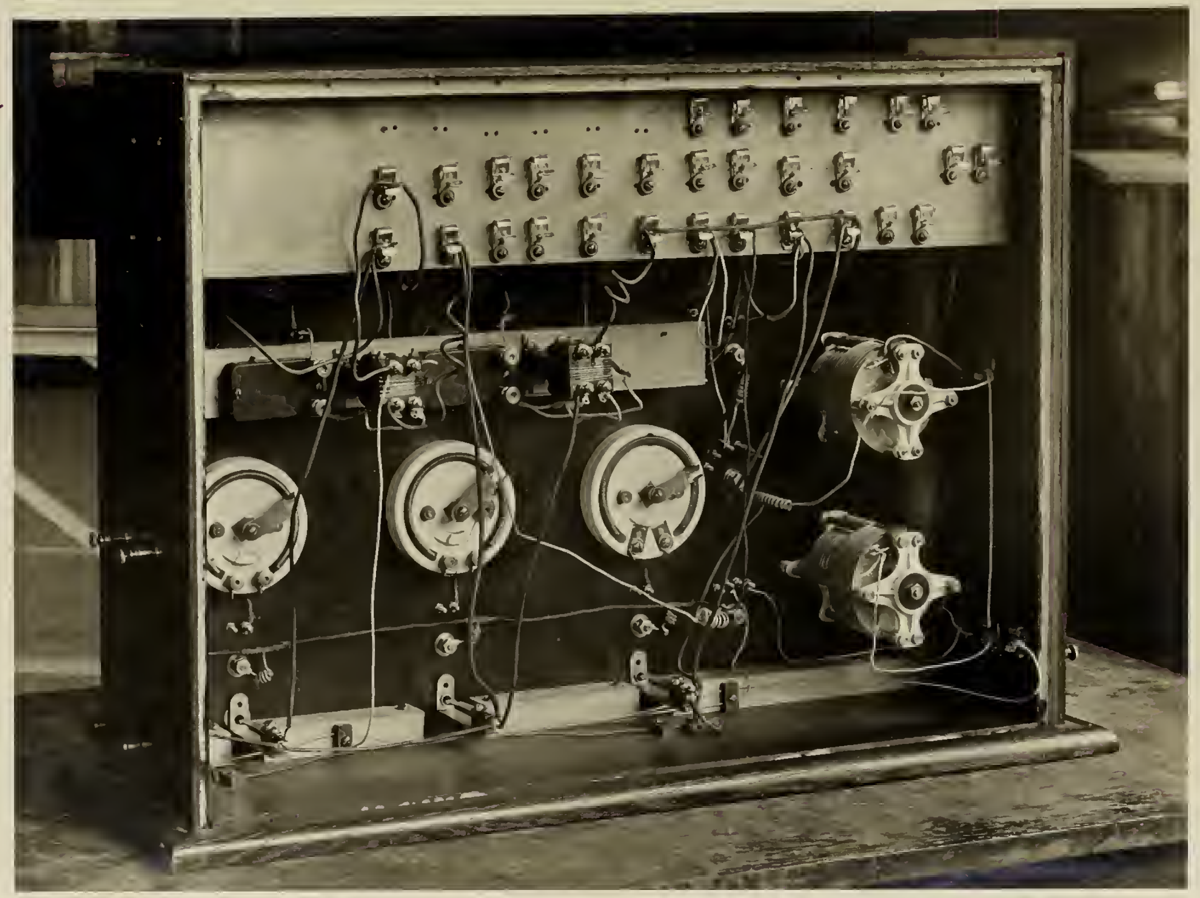
Fig. 81.

Cabinet Receiver Wiring Diagram.





Receiver - Front View.



Receiver - Rear View.

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[illegible]
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II. Special Equipment for Radio Laboratories.

The special equipment required for the laboratory course outlined in this thesis is not costly if selected with care. Perhaps the most costly item is that of providing sources of current for the vacuum tube circuits. Six volt, 50 ampere hour storage batteries are necessary for filament current. For plate circuits battery voltage is more satisfactory than that from generators or dynamotors on account of the steady voltage and quietness of the circuit. The small dynamotors manufactured for this purpose are subject to excessive heating if two or more transmitting tubes are used in parallel. Many types of small high voltage batteries for receiving tubes are on the market, and have one of two disadvantages; they are either costly or they have a shelf life of a few months. The writer has found that a very efficient and lasting battery can be made from a type of dry cell which has a hollow carbon electrode with a cork at the top. This type of cell is put into service by filling with water until it has absorbed as much as possible. Thirty six of these cells are placed in a closed box and fuses provided for protection. Three one half ampere fuses should be provided, one in series with each terminal and one between each half of the group of cells. Two of these batteries in series provide 110 volts. The oscillator for capacity measurement, and the laboratory radiophone described in the laboratory course have been used by the writer with fair success using the above voltage.

The requirements of this course are admirably met by using the small Western Electric Company transmitting tubes. The figures given for the oscillator circuits used are obtained with this type. A certain type of small vacuum tube advertised for use as an oscillator by its makers will furnish .3 ampere in the laboratory oscillator with a plate potential of 500 volts, which compares favorably with the tube mentioned previously. Much trouble was experienced by the writer in attempting to use this latter type of tube due to the fact that the high voltage would often soften the tube making it useless for further use. If these tubes are used it is necessary to have them specially tested by the makers. The high output vacuum tubes have not been considered for this course on account of their high cost, and on account of the expense of providing 1500 volts for the plate circuits. The constants of the Western Electric transmitting tube are given in the Table on the following page.

CHARACTERISTICS OF #305-B VACUUM TUBE

Use	Amplifier	Oscillator	Modulator
Normal Filament Current	1.35 amperes	1.35	1.35
Normal Filament Voltage	6.5 to 7.5 volts	6.5 to 7.5	6.5 to 7.5
Normal Plate Voltage	350 volts	350	350
Normal Grid Voltage	-20 volts	Variable	-20 volts
Voltage Amplification Constant	6.5 to 7.5	6.5 to 7.5	6.5 to 7.5
Normal Plate Current	35 to 55 milli-amperes	40 to 50	35 to 55
High Frequency Output		5.5 to 6 watts	
Output Impedance for Plate Voltage 350 and Grid -20	3000 to 4500 ohms		
Average Useful Life			
at 1.35 amperes	175 hours	175	175
at 1.30 amperes	350 "	350	350

The above voltages are measured from the negative end of the filament.

When used as an amplifier the grid voltage should not be less negative than the peak value of input voltage, and the plate battery should be increased above normal by an amount equal to the product of the grid voltage by the voltage amplification constant, in order not to cause distortion.

For more complete information see Dr. H. J. Van der Bijl's paper on the "Theory of the Thermionic Amplifier" in the Physical Review, N. S., Vol. XII, No. 3, September, 1918.